INVESTIGATION OF ARM POSTURE MAPPING USING VIBROTACTILE FEEDBACK

Submitted by

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Abstract

A significant number of people suffer from stroke each year. For those who survive, the ability to carry out skilled upper limb movement are afflicted with motor control problem. Hence, it is necessary to provide them rehab exercises to recover the upper limb's movement. Most rehabilitation involves having the patients repeat arm movements or train to achieve correct different arm postures. Due to the increasing number of patients in rehabilitation centers, developing a home-based low cost device is valuable and important for arm posture replication and rehabilitation. In recent years, the vibrotactile feedback has been used widely in post-stroke rehabilitation. This research concerns the investigation of protocol, and strategies of utilizing vibrotactile feedback for the arm posture replication. In particular, the main focus of project is to investigate the best strategy in term of mapping time and accuracy for an integrated system comprising IMU and vibrotactile feedback in arm posture replication. The new protocol models the arm posture using three parameters – the wrist position, the elbow position, and the forearm's roll. The arm motion is captured by using IMUs attached to the forearm and the upper arm, while tactile feedback is provided by vibrotactor unit located on the forearm. Four feedback modes are cosidered – visual only, tactile only, visual and tactile in series (series visuotactile), and visual and tactile in parallel (parallel visuotactile). Two different ways of using vibrotactile feedback, as directional indicator and as posture error indicator, for arm posture replication are also investigated. Two sets of experiments conducted and the collated data are analyzed using specially developed software. Interesting results are obtained from experiments. A series visuotactile mode provides slightly better performance (faster 9s compared to parallel visuotactile mode, 15s compared to tactile only mode; the mapping accuracy is approximately the same among 3 modes). The directional feedback on stationary arm provides better performance compared to using it on moving arm (faster 6s to complete the posture correction; however, the mapping errors between two approaches, either on stationary or moving arm are comparable). Lastly, the usage of vibrotactile feedback as matching error indicator enables faster (16s) and more accurate (8mm for wrist position) arm posture correction than the directional feedback on moving arm.

Key words: *visuotactile feedback* - *vibrotactile feedback* - *directional feedback* - *arm posture correction*

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Chapter 1: Introduction

1.1 Background

A stroke causes damage to the brain. A common cause of stroke is a blood clot that forms in a brain artery. Immediate treatment may include a clot-busting medicine to dissolve the blood clot. Other treatments include medication to reduce risk factors for further strokes. Rehabilitation is a major part of treatment. According to the World Health Organization Report in 2002, 15 million people worldwide suffer from stroke each year and approximately two thirds of these individuals survive and require rehabilitation [1].

The goals of rehabilitation are to help survivors become as independent as possible and to attain the best possible quality of life. Even though rehabilitation does not "cure" the effects of stroke in that it does not reverse brain damage, rehabilitation can substantially help people achieve the best possible long-term outcome. Hospitals which deal with stroke patients have various specialists who help in rehabilitation. These include: physiotherapists, occupational therapists, speech therapists, dieticians, psychologists, specialist nurses and doctors. One or more of these may be required, depending on how the stroke has affected. Good-quality rehabilitation is vital following a stroke, and can make a big difference to your eventual outcome.

Stroke patient's ability to carry out skilled upper limb movements like daily living activities are afflicted with motor control problems [2]. Therefore, most rehabilitation involves having the patients repeat arm movements or train to achieve correct different arm postures. Due to the increasing number of patients in rehabilitation centers, it is necessary to develop a home-based low cost device for arm posture replication and rehabilitation. Home rehabilitation allows for great flexibility so that patients can tailor their program of rehabilitation and follow individual schedules. The major disadvantage of home-based rehabilitation programs is the lack of specialized equipment. This device can guide the user in the training process with minimal therapist involvement.

1.2 Objective and Scope

The system for arm posture replication involves motion captures and motion indicator (providing feedback information). For this research, two motion capture modules, inertial motion units named as IMUs are worn on the forearm and the upper arm respectively by a master; another two IMUs with two motion orientation indicators are worn in the same way by a student. The motion indicator then generates different vibration patterns based on this input and gives users a tactile feedback in directing their movements. The student is able to track and follow the master's forearm and upper arm movement in any postures, as shown in Fig.1-1.

The first objective of this project is to implement the new protocol for arm posture replication, by evaluating the mapping time and the accuracy, following the mapping order: the wrist position, the elbow position and the forearm's roll. On the other hand, to further the capability of robotic rehabilitation, the incorporation of the proper feedback mode for motion indicator is necessary. There are several kinds of feedback such as: tactile, vision and sound feedbacks. Designing the appropriate combination of feedback channels is an important step. Therefore, the second objective is to find the best strategy for the posture correction, in terms of the mapping time and the accuracy.

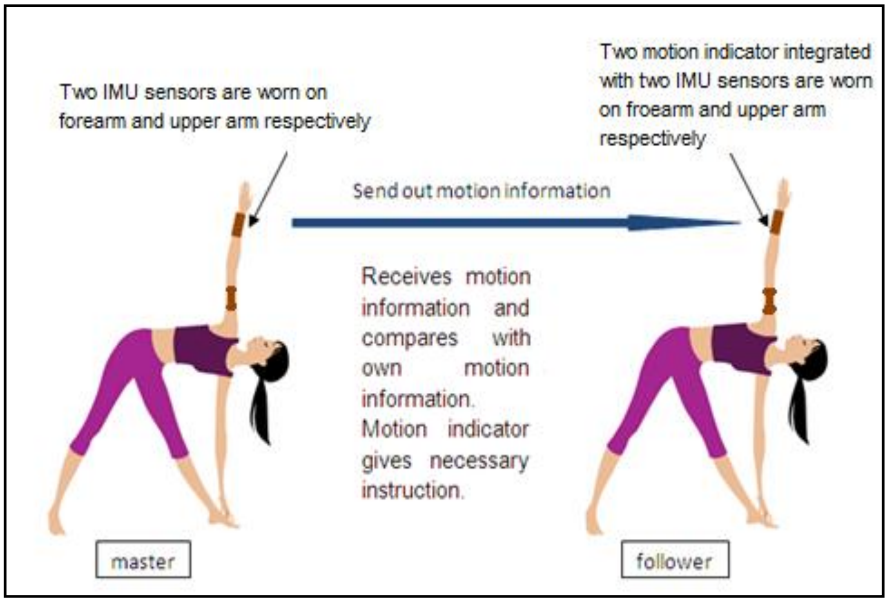


Figure 1- 1: Demonstration of one application of the integrated motion tracking device

The scope of this project covered:

- Implementing new protocol for correcting the arm posture. Developing a graphic user inferface (GUI) software with user interface as control system for the integrated system with IMU and vibrotactile feedback unit.
- Investigating and analysing the use of vibrotactile sensor as direction or matching error indicators.
- Investigating and analysing different combinations of visual and vibrotactile feedback.

1.3 Organization of the report

In this research, a motion tracking device has been developed based on the integration of motion capture module and tactile feedback indicator. The report attempts to present the entire design procedures of this kit. The whole report consists of six chapters:

- Chapter 1: gives background, objective and scope for this project as well as organization of the report.
- Chapter 2: briefs review about current advanced technologies for motion capture devices and recent research on vibrotactile feedback, motivation of current work.
- Chapter 3: introduces the model of arm posture and software development.
- Chapter 4: investigates the use of vibrotactile feedback as direction or matching error indicator.
- Chapter 5: investigates different combinations of visual and vibrotactile feedback.
- Chapter 6: summarizes the whole project and recommendations for future work.

Chapter 2: Literature Review

In order to replicate a reference arm posture, it is necessary to measure arm posture accurately and provide timely feedback to the user. Therefore, the capture motion devices as well as feedback are incorporated to correct any arm posture. In this chapter, we will have a quick review about currently available technology for motion capture devices and recent research on vibrotactile feedback.

2.1 Motion capture devices

For the motion tracking system, those available technologies now include: optical system (vicon tracking) and non-optical system (magnetic motion capture, mechanical motion capture, inertial motion capture).

2.1.1 Optical system

Optical motion capture systems tend to utilize proprietary video cameras to track the motion of reflective markers (or pulsed LED's) attached to particular locations of the actor's body. Single or dual camera systems are suitable for facial capture, while 8 to 16 (or more) camera systems are necessary for full-body capture. There are two method used in optical motion capture which are Passive optical system and Active optical system. Passive optical motion capture systems use Infra-red (IR) LED's mounted around the camera lens, along with IR pass filters placed over the camera lens. Active optical motion capture systems based on Pulsed-LED's measure the Infra-red light emitted by the LED's rather than light reflected from markers [34]. Optical motion capture systems have the advantage of being very configurable (you can put the markers on an elephant or fabric, or baseballs or footballs, etc.) A large active area is possible, depending on budget and space limitations. Optical systems are useful for capturing gymnastic types of moves. Optical motion capture is most often used “out of house” at specialty studios, but is very popular for animation for sports games as well as motion capture for film.

The Vicon Tracking system is the most popular optical motion tracking system which is designed by Vicon, Inc. [35]. This system is an automated motion capture system that tracks the position of infra-red reflective markers in space. The basic set-up of the system includes about one dozen of high-resolution cameras, one dozen of matched infra-red circular strobes, and some custom hardware as shown in Fig.2-1. The Passive markers which are coated with a retro-reflective material are placed directly on human body and are illuminated by the strobes. By going through filters, only the bright reflections are visible, ignoring skin and fabric. After calibrating the cameras' locations in the software, the 3-D models of all markers can be obtained from the individual 2-D camera views. Subject skeletal figure can be modeled through the software based on the location of the markers, and all the joint positions are inferred based on which joint angles are calculated. The software also provides a function of calibration for different people with different joint length in order to analyze different subjects with same skeletal model.

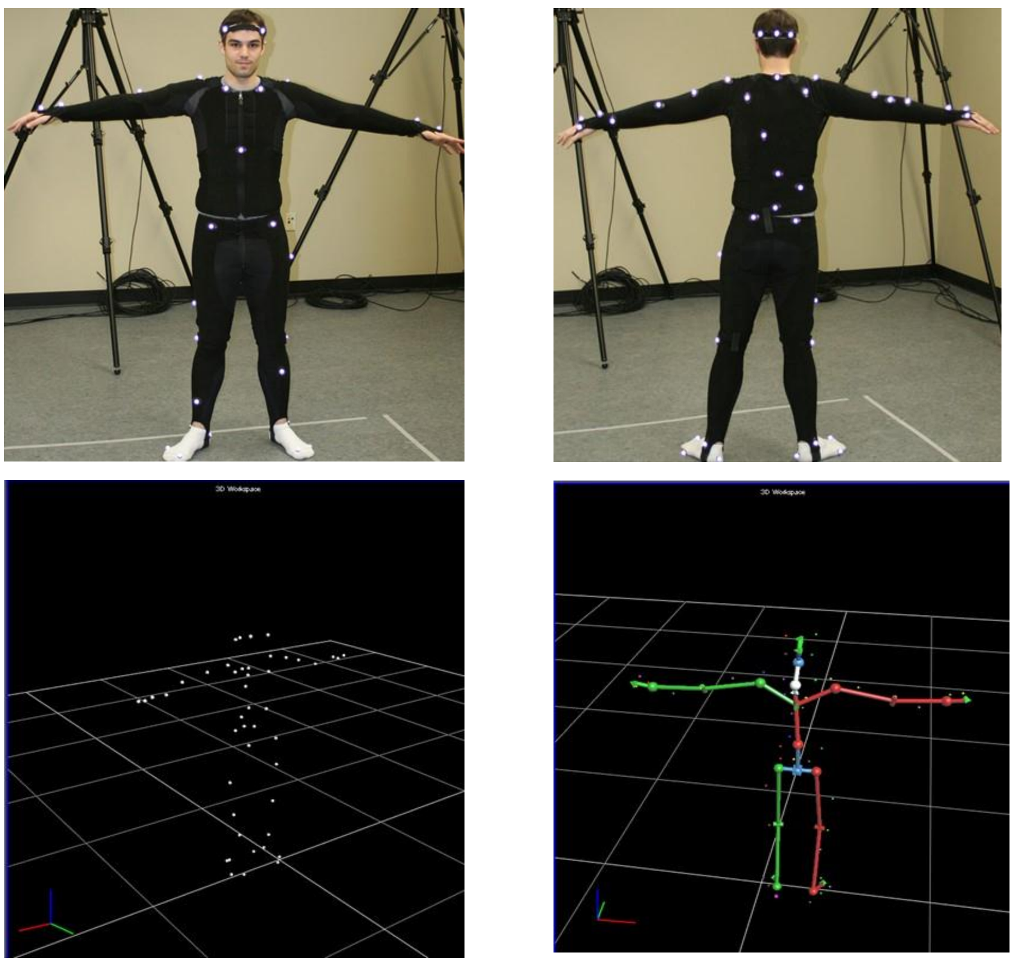


Figure 2- 1: Working mechanism of the Vicon motion capture system [35]

2.1.2 Non-optical system

There are three main technologies used in non-optical motion capture: mechanical motion, magnetic systems, and inertial systems.

a. Mechanical motion capture systems

Mechanical motion capture systems utilize sensors (Goniometers) attached to the body to directly track body joint angles as shown in Fig.2-2. Performer attaches the skeletal-like structure to the body, and each joint is then connected to a goniometer. These angle measuring devices provide joint angle data to kinematic algorithms which are used to determine end effect or position as well as body posture. But the system is limited by mechanical constraints related to the implementation of the sensors and the exoskeleton, there is much more difficult to move with a fairly heavy exoskeleton, so the freedom of movement is rather limited. Furthermore, the sampling rate for this kind of system is also low [38].

Figure 2- 2: GypsyMIDI mechanical motion capture system

b. Magnetic motion capture systems

Magnetic motion capture systems utilize non-metallic sensors (markers) placed on the body to measure the magnetic field generated by a transmitter source (field emitter assembly). The sensors are cabled to an electronic control unit that correlates their reported locations within the field. The sensors contain three mutually perpendicular coils. As the coils are moved through the magnetic fields, the induced current within them will change. These changes in strength across the coils are proportional to the distance of each coil from the field emitter assembly. The emitter assembly is also constructed of three mutually perpendicular coils that emit a magnetic field when a current is applied. Current is sent to these coils in a sequence that creates three mutually perpendicular fields during each measurement cycle. In all nine induced currents are generated within the sensor coils and used to calculate a position and orientation. Each of the three emitted fields creates one induced current in each of the three sensor coils, thereby allowing measurement of the nine elements of a rotation matrix associated with each sensor [36].

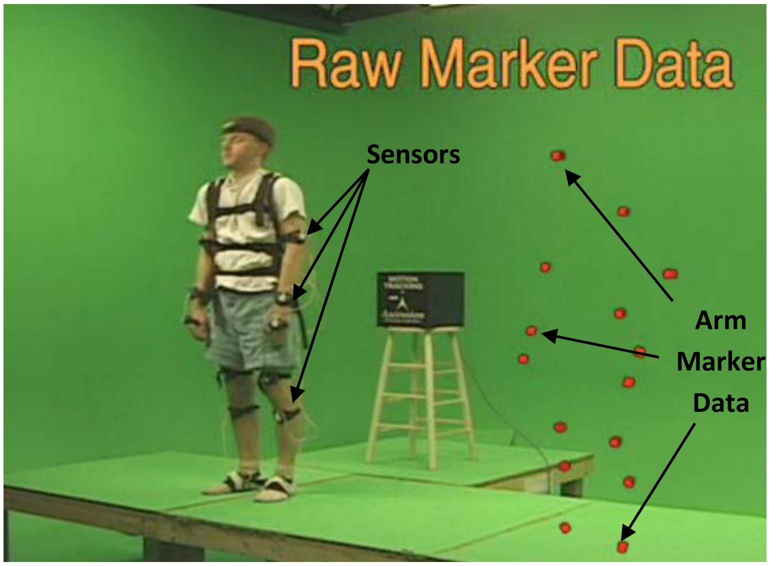


Figure 2- 3: Magnetic motion capture systems with the raw marker date [36]

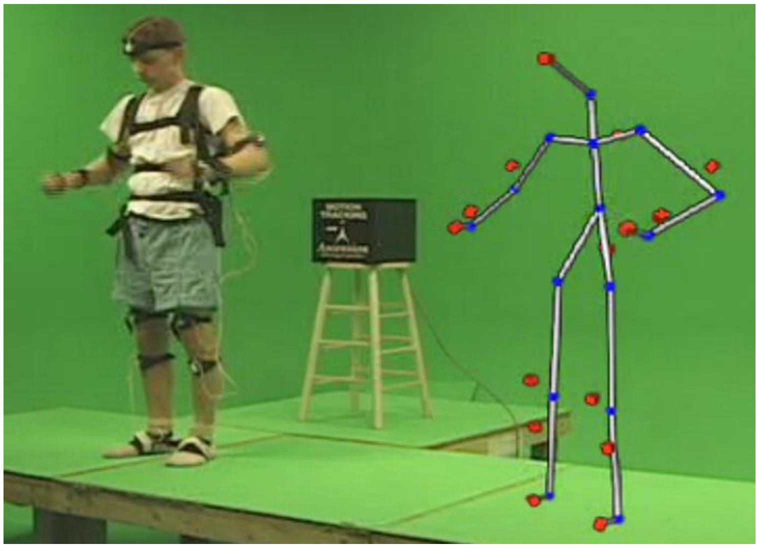


Figure 2- 4: Magnetic motion capture systems with the hierarchical structure [37]

One example is shown in Fig.2-3, there is one sensor on the upper arm and one sensor on the lower arm of the person, and they are able to find the elbow position and angle. The sensor on hand with the lower arm sensor can define the wrist position and angle. The systems analyze all the data which are captured in relation to the source in real time. The limb lengths, joint locations, and sensors placement can be determined. By computing these parameters through performing a linear least squares fit of a rotary joint model to the input data, a hierarchical structure for the articulated model can also be determined as shown in Fig.2-4 [37].

c. Inertial motion capture systems

Current technology has introduced an Inertial Measurement Unit (IMU) that is able to measure correctly body posture and motion with the combination of accelerometers, gyroscopes and magnetometers. Each IMU provides real-time orientations and calibrated 3 DOF linear accelerations (from the accelerometer), 3 DOF angular velocities (from the gyroscopes) and 3 DOF magnetic data (from the magnetometer). The data from nine sensors yields the roll, pitch, and yaw angles of the IMU itself. The accelerometer is a dual-axis low *g* MEMS-based capacitive ADXL320 from Analog Devices. It is capable of measuring linear acceleration signals over a bandwidth of 60 Hz and has an effective sensing range of *2g – 6g*. The magnetometer is a tri-axis magnetic field sensing module HMC1053 from Honey Well. It has a measurement range of 6 Gauss and capable of measuring the geomagnetic vector. The pair of gyroscopes, dual-axis gyroscopes from Silicon Sensing System (Japan), measures tri-axis angular velocities with a measurement range of 300^o/sec in yaw, and 500^o/sec in roll and pitch. The IMU is shown in Fig.2-5.

Figure 2- 5: Sample of an inertial motion control unit

Based on previous research, the IMU can be used to determine gait kinematics [3], measure trunk and wobble board displacements [4], and full body motion [5]. Moreover, it also has been employed effectively in rehabilitation by detecting and assessing severity of Parkinson's disease [6], quantifying hemiparesis by measuring hand path in pointing tasks [7], and treating idiopathic scoliosis [8].

The advantages as well as disadvantages of the various systems are summarized in Table 2-1.

Table 2- 1: Comparison of motion capture system

	Motion System	Advantage	Disadvantage
Optical system	*Vicon Tracking System*	• performer feels free to move due to no cables connecting body to the equipment • very clean, detailed data • stable and high accuracy	• reflective dots can be blocked by performers or other structures, causing loss of data • limited coverage areas • require line-of-sight links • higher cost
Non-Optical system	*Magnetic motion capture systems*	• positions are absolute, rotations are measure absolutely; orientation in space can be determined • no limitation to line-of-sight links • relatively cheaper than optical	• limiting tracking area • the field is easily distorted by ferrous objects in the surrounding area • low sampling speed
	Mechanical motion capture systems	• no interference from light or magnetic fields • self-contained	• equipment must be calibrated often • cumbersome to wear • not flexible for joints with multiple degrees of freedom
	Inertial Motion Capture systems	• self-contained system • limitless tracking • no need to provide extensive infrastructure • low cost	• noisy sensed data causes cumulative errors to build up

2.2 Recent research on vibrotactile feedback

Not only based on tracking motion system, in order to achieve the fast-response and intuitive feedback, there are few researches done in the designing of a motion indicator. The feedback can be audio feedback, visual feedback or tactile feedback.

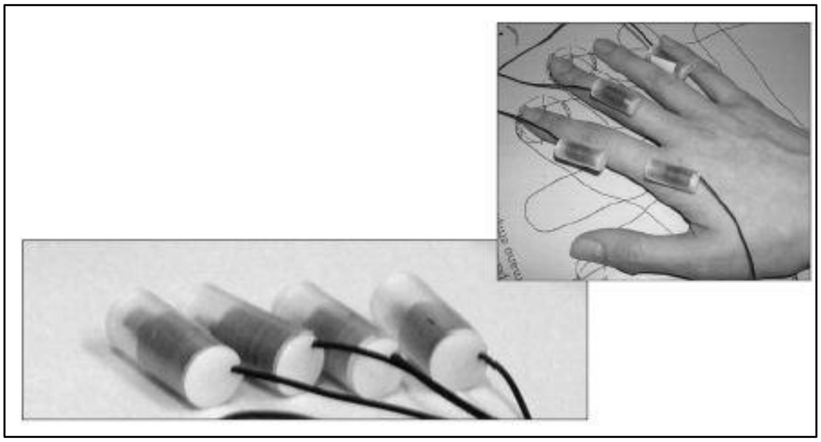


Figure 2- 6: Personal vibrotactile stimulator for rehabilitation of the hand in stroke and Parkinson patients [10]

As such, this project focuses on the design of a motion tactile feedback indicator. The vibrotactile feedback involves an important role in rehabilitation. The research in [9] presents a comprehen-sive review of the technological enhancements of vibrotactile in rehabilitation, sports and information display domains. The vibrotactile feedback has significant contributions as stimulator for rehabilitation of the hand in stroke and Parkinson patients [10], as wireless sensory feedback system for real-time gait modification [11], balance training [12] [13], motor learning [14], as risk fall indicator for trunk [15], as feedback for gesture correction for upper body [16], motion replication for arm [17] [18], and seated posture guidance [19].

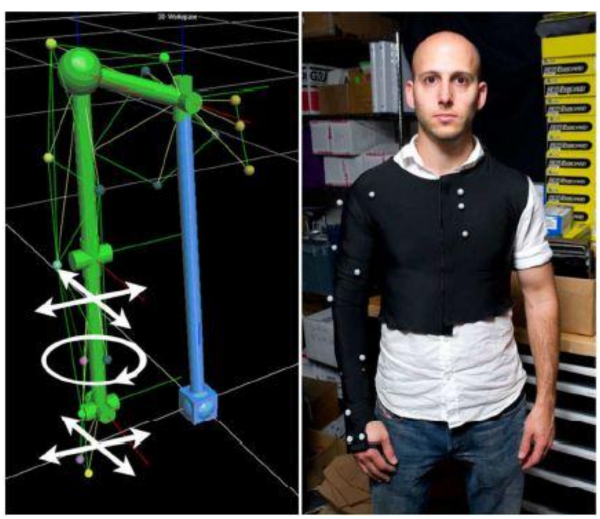


Figure 2- 7: Development of a wearable vibrotactile feedback suit for improved human motor learning [14]

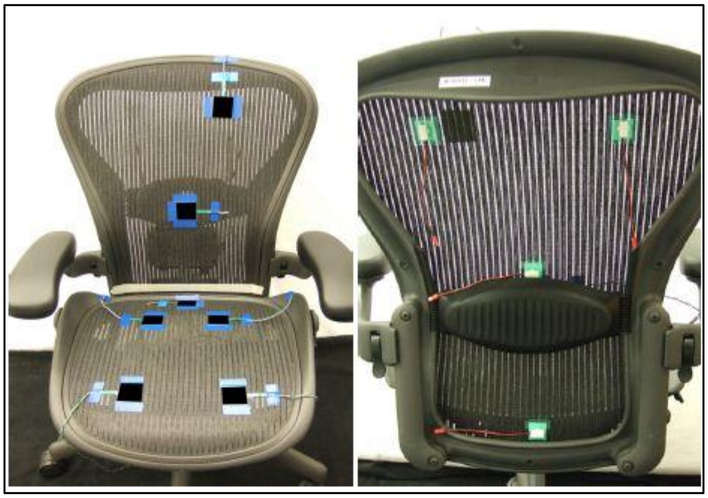


Figure 2- 8: A vibrotactile feedback approach to posture guidance [19]

With advanced technology, the tactor becomes very compact, functional with variety range of application. In this project, the small flat type (VPM2) actuators (tactors) is employed as shown in Fig.2-9, the small transducers designed to optimize skin response to vibration.

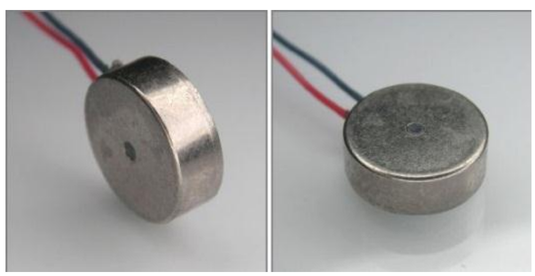


Figure 2- 9: VPM2 tactor

Each tactor, manufactured by Solarbotics (Calgary, Canada), is activated at the 80Hz to 250Hz frequency range and converts electrical energy into mechanical displacement by using DC power to rotate an eccentric weight. With a 3V driving voltage, each tactor is able to generate 1*g* (9*:*8*m/s*2) acceleration vibration level, which is higher than the discrimination thresholds of the forearm and the upper arm, 0.6*g* and 0.8*g*, respectively [32]. Some detailed characteristics of VPM2 are listed in the table (Table 2-2) and the figure (Fig.2-10).

Table 2- 2: Specifications of VPM2

Diameter (mm)	12
Thickness (mm)	3.4
Weight (g)	1.23
Standard Voltage (V)	3
Operating Voltage (V)	2.5 to 3.5
Power Supply	DC (battery)
Standard Speed (rpm)	12±3

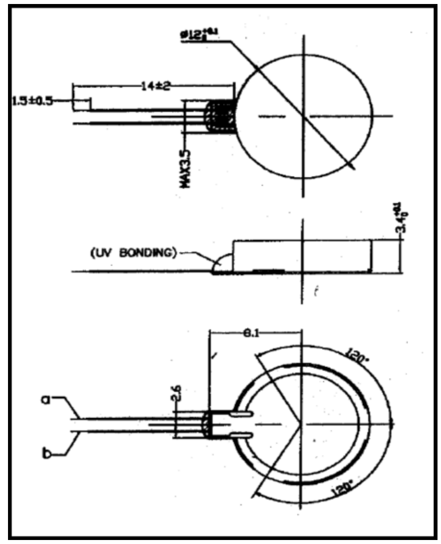


Figure 2- 10: Dimensions of VPM2

For the feedback, different modes are available for correcting posture or for the rehabilitation in general. A feedback mechanism combining vision and audio was developed for stroke patient rehabilitation [20]. In [14], the audio and the visual cues given by the teacher are aided by a robotic suit that employed tactile feedback to guide the movement of the upper limb of the students. For a more robust Tai-Chi performance of the users, the vibrotactile feedback is complemented with audio feedback [16]. Combination of vision and tactile feedback has been employed in [21] to enhance the motor performance of the user. The vision is combined with haptic feedback for rehabilitation of children's upper extremity [22]. In [23], [17], and [24], the visual and tactile feedback are used to guide the subjects in replicating the target arm posture. In [25], the audio feedback is added as well for better virtual reality based rehabilitation. The key idea to remember in choosing the combination of the feedback is that the time delay between sending the signal and responding to the signal should be shortened [26]. More importantly, it has been shown that selecting the proper feedback could affect the outcome of stroke patient rehabilitation [27]. The studies have shown that using virtual reality and haptic feedback as training device provides better outcome for rehabilitation of stroke patients [28]. A review of recent advances in upper limb stroke rehabilitation using various technologies can be found in [29]. This project examines the posture correction performance of several subjects in terms of mapping time and accuracy when using different feedback modes that include visual cue and vibrotactile.

For replicating upper limb posture, the use of vibrotactile feedback in providing directional versus non-directional vibrotactile feedback is a fundamental issue to be resolved. Few researches on that explore directional feedback using vibrotactile actuators exist: instruction of arm motion for calligraphy in 2D-plane [30], design of arm posture mapping and replication system in 3D [31]. This research also focused on the development of an arm posture correction system that uses directional information from haptic feedback then compare the usages of vibrotactile feedback to provide direction and non-direction indicators in order to replicate arm posture.

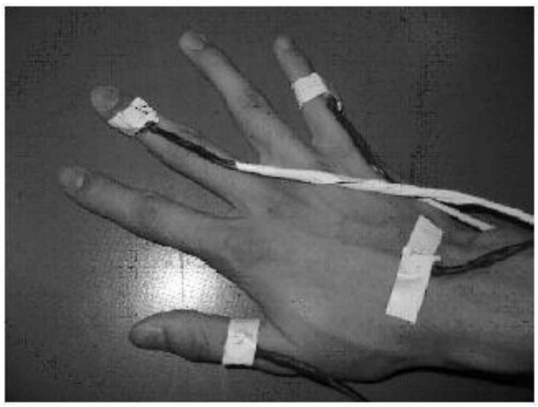


Figure 2- 11: Instruction of arm motion for calligraphy using vibrotactile stimulations [30]

2.3 Motivation of current work

Based on the surveys, there is a gap in which the integrating motion capture device with vibrotactile feedback for upper limb rehabilitation has not been given much attention. From quick review of current available motion capture technology, the IMU with low cost, compactness and high sensitivity can be utilized for desired system. The vibrotactile feedback seems to be a promising approach in rehabilitation. Up to now, there is few research focuses on evaluating the usages of vibrotactile feedback as directional and non-directional indicators, as well as incorporating tactile feedback with the other kinds of feedback such as: visual feedback, audio feedback. Therefore, it motivates us in conducting this research, to figure out the best strategy for upper limb rehabilitation by using integrated system with IMU and vibrotactile feedback. The results of this research are really necessary in contributing to the post-stroke rehabilitation.

Chapter 3: Arm Posture Modeling and Software Development

In this chapter, the arm posture is modeled by obtaining orientation information from the IMUs attached to the upper arm and the forearm. Three parameters to determine the correct posture are: the wrist position, the elbow position and the forearm's roll. The kinematic model of the arm is formulated for determining the wrist and elbow positions in 3D Cartesian coordinate originated at the subject's shoulder. Using kinematic formulation, the software with user interface is developed in C++ to guide the subjects during posture replication.

3.1 Protocol for arm posture replication

The arm posture is corrected one parameter at a time in the following order:

a) 3D position of the wrist (x_f ; y_f ; z_f)
b) 3D position of the elbow (x_u; y_u; z_u)
c) Forearm roll (φ_f)

A user's current posture is considered matched to a reference posture if all the parameters are within specified thresholds. This protocol can also be considered to be more natural than previous posture correction strategies implemented in [23] and [17]. In those previous works, arm posture was corrected one parameter at a time starting from the shoulder to the forearm. However, this process is more mechanical compared to correcting from the wrist and elbow first (gross motion correction followed by fine motion adjustment), which mimics human behavior more closely.

3.2 Arm posture kinematics

Illustrated in Fig.3-1, the arm is modeled with two rigid segments, each having range of motion and capable of bending and rotating in three dimensions. Two sets of yaw, pitch and roll angles of the upper arm and the forearm can be formulated by using kinematic model to determine the wrist position, the elbow position with respect to the shoulder.

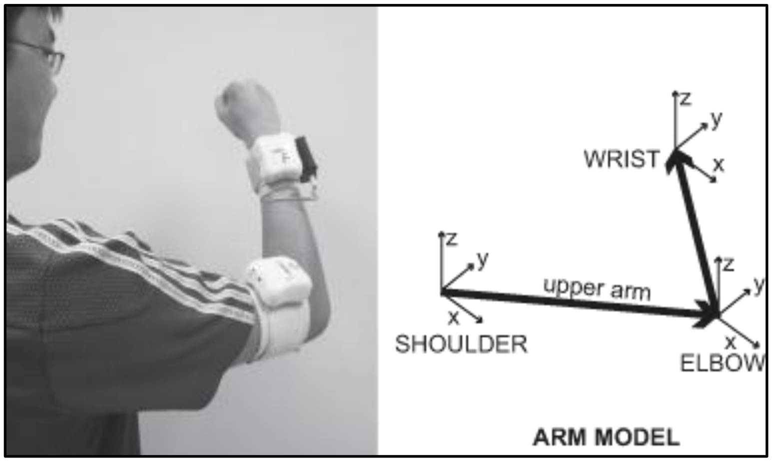


Figure 3- 1: Arm modeling

Using the proposed kinematic model, the wrist and the elbow positions can be evaluated by yaw, pitch and roll angles of the upper arm and the forearm. There are many methods for describing the rotating rigid bodies. The commonly used method is Candan angles. Here the Z-Y-X Candan angles is applied. The direction of the global system X-Y-Z is placed with other coordinate systems shown in Fig.3-2 to perform the further transformation [23]. A sequence of rotations is performed to translate the X-Y-Z coordinates to coincide with the x_3-y_3-z_3 coordinates. The process of this transformation is to rotate about the Z axis by an angle φ, and obtain the x_1-y_1-z_1 coordinates. After that, the rotation about Y axis translates the x_1-y_1-z_1 coordinates to x_2-y_2-z_2 coordinates. Finally, the rotating about the X axis is used to translate the x_2-y_2-z_2 coordinate to x_3-y_3-z_3 coordinates. The transformational equations based on Candan angles method are listed below. The rotations along Z, Y, X are also named the yaw, the pitch and the roll [24] as shown in Fig.3-3.

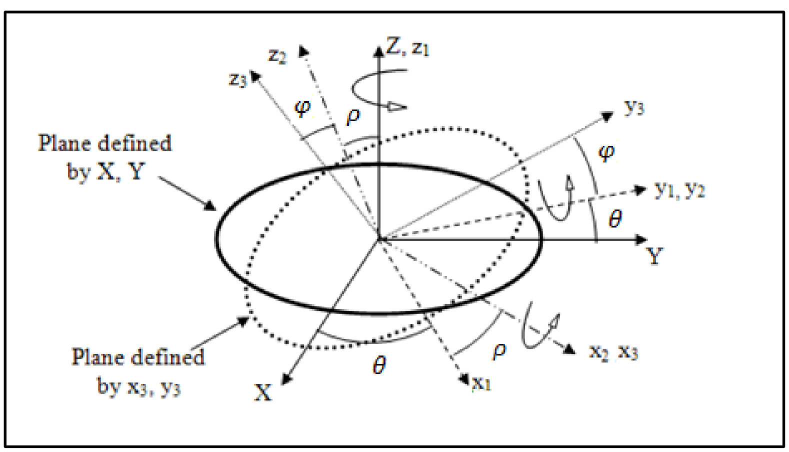


Figure 3- 2: Candan Angles of an IMU

$$\begin{Bmatrix} x_1 \\ y_1 \\ z_1 \end{Bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} \text{; Yaw Rotation} \qquad (1)$$

$$\begin{Bmatrix} x_2 \\ y_2 \\ z_2 \end{Bmatrix} = \begin{bmatrix} \cos\rho & 0 & -\sin\rho \\ 0 & 1 & 0 \\ \sin\rho & 0 & \cos\rho \end{bmatrix} \begin{Bmatrix} x_1 \\ y_1 \\ z_1 \end{Bmatrix} \text{; Pitch Rotation} \qquad (2)$$

$$\begin{Bmatrix} x_3 \\ y_3 \\ z_3 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix} \begin{Bmatrix} x_2 \\ y_2 \\ z_2 \end{Bmatrix} \text{; Roll Rotation} \qquad (3)$$

To translate from x_3-y_3-z_3 coordinates back to the global coordinates X-Y-Z; we have the rotation matrix given by:

$$R = \left\{ \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} \cos\rho & 0 & -\sin\rho \\ 0 & 1 & 0 \\ \sin\rho & 0 & \cos\rho \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \right\}^{-1} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

Finally we obtain the rotation matrix that transforms 3D orientation (yaw, pitch, roll) of each arm segment to its global system:

$$R(\varphi, \rho, \theta) = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \qquad (4)$$

Where,

$$r_{11} = cos(\varphi)cos(\rho)$$

$$r_{12} = sin(\varphi)cos(\theta) + cos(\varphi)sin(\rho)sin(\theta)$$

$$r_{13} = sin(\varphi)cos(\theta) - cos(\varphi)sin(\rho)sin(\theta)$$

$$r_{21} = -sin(\varphi)cos(\rho)$$

$$r_{22} = cos(\varphi)cos(\theta) - sin(\varphi)sin(\rho)sin(\theta)$$

$$r_{23} = r_{22} = cos(\varphi)cos(\theta) + sin(\varphi)sin(\rho)cos(\theta)$$

$$r_{31} = sin(\rho)$$

$$r_{32} = -cos(\rho)sin(\theta)$$

$$r_{33} = cos(\rho)cos(\theta)$$

We can locate the position of the wrist (x_f ; y_f ; z_f) and the elbow (x_u; y_u; z_u) with respect to the shoulder, assuming that its position remains fixed during arm movement. Using the rotation matrix equations (4) with the orientations of the upper arm (φ_u, ρ_u, θ_u) and the forearm (φ_f, ρ_f, θ_f), the elbow and wrist positions can be obtained as following equations:

$$\begin{bmatrix} r_{11}^u & r_{12}^u & r_{13}^u & 0 \\ r_{21}^u & r_{22}^u & r_{23}^u & 0 \\ r_{31}^u & r_{32}^u & r_{33}^u & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L_u \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} x_u \\ y_u \\ z_u \\ 1 \end{bmatrix} \qquad (5)$$

$$\begin{bmatrix} r_{11}^f & r_{12}^f & r_{13}^f & x_u \\ r_{21}^f & r_{22}^f & r_{23}^f & y_u \\ r_{31}^f & r_{32}^f & r_{33}^f & z_u \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L_f \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} x_f \\ y_f \\ z_f \\ 1 \end{bmatrix} \qquad (6)$$

where L_f is the forearm length and L_u is the upper arm length.

3.3 IMU measurements

To figure out the positions of the wrist and the elbow with respect to the fix shoulder, it is necessary to know the yaw, pitch and roll angles of the upper arm and the forearm. An IMU is attached to each arm segment, assumed to be massless, for orientation measurements: yaw, pitch and roll angles. The IMUs are attached near the elbow and the wrist, as shown on the left photo in Fig.3-1. The subject will be trapped into chair during experiment, therefore the shoulder will be considered at fixed position.

3.3.1 Yaw, Pitch and Roll angles

An IMU packs 9 sensors (3 accelerometers, 3 angular rate gyros, 3 magnetometers) that precisely and accurately measure motion in 3 dimensions. In this IMU orientation system, the directions of X, Y, Z are towards north, east and down to the center of the earth respectively and the origin is arbitrarily selected on the surface of the Earth. The rotations of subject along the X, Y, Z axes are called Roll (φ), Pitch (ρ) and Yaw (θ) accordingly (shown in Fig.3-3).

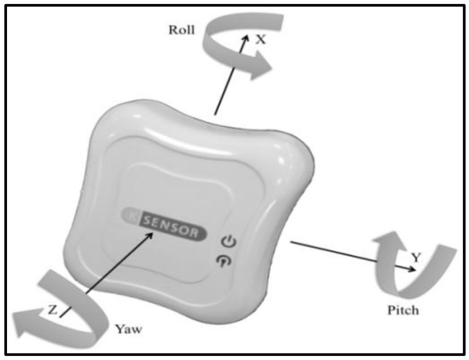


Figure 3- 3: Directions of X,Y,Z in of IMU a global system

The orientation of the IMU with respect to its global system, [$\varphi_{imu}(t)$ $\rho_{imu}(t)$ $\theta_{imu}(t)$], is derived from the angular velocities [ω_x ω_y ω_z] about the three axes of the gyroscope. The angular displacements are calculated by integrating the angular velocities:

$$\varphi_{gyro} = \int_{t_i}^{t_f} \omega_x \, dt$$

$$\rho_{gyro} = \int_{t_i}^{t_f} \omega_y \, dt$$

$$\theta_{gyro} = \int_{t_i}^{t_f} \omega_z \, dt$$

Given the angular value at $(t - 1)$ and Δt, the numerical approximation becomes:

$$\varphi_{gyro}(t) = \varphi_{gyro}(t-1) + \omega_x \, \Delta t$$

$$\rho_{gyro}(t) = \rho_{gyro}(t-1) + \omega_y \, \Delta t$$

$$\theta_{gyro}(t) = \theta_{gyro}(t-1) + \omega_z \, \Delta t$$

The IMU uses the accelerometer measurement to correct for the gyroscope integration error.

Each IMU sensor uses a global coordinate system through its magnetometer measurement of the earth’s magnetic north as reference. Thus, the IMUs have to be calibrated to the arm coordinate system to negate the effect of user orientation. The arm’s reference axis is located at the shoulder, the X-axis is parallel to the body plane, the Yy-axis is perpendicular to the body along the arm and the Z-axis is against the gravity vector.

3.3.2 Calibration

To calibrate the IMUs, the user has to stretch his arm forward so that it is perpendicular to the plane of the body with the elbow angle at 180^0, as shown in Fig.3-4. Then, the orientations of IMUs are recorded as (φ_{u_offset}, ρ_{u_offset}, θ_{u_offset}) for upper arm and (φ_{f_offset}, ρ_{f_offset}, θ_{f_offset}) for the forearm. Therefore, for each obtained set of the IMUs from either the upper arm or the forearm, we need to offset the orientation angle by (φ_{u_offset}, ρ_{u_offset}, θ_{u_offset}) for the upper arm and (φ_{f_offset}, ρ_{f_offset}, θ_{f_offset}) for the forearm before handling the rotation matrix.

Figure 3- 4: Calibrating the IMUs on the arm prior to every experiment

3.4 Software development

The developed software will corporate the motion captures (IMU) with vibrotactile feedback to assist the arm replication in rehabilitation. The software with Graphic User Interphase (GUI) provides different options for whole set of experiments in this project. The details of software development are presented in this section.

3.4.1 System overview

The Fig.3-5 shows the system overview for software development. The GUI feature of the software provides a variety of options for several of experiments such as: selecting posture number, subject number for data recording purposes; incorporating visual feedback with vibrotactile feedback, or just visual feedback only, vibrotactile feedback only; using vibrotactile feedback as directional indicator or providing matching error and so on. More descriptions are discussed in section 3.4.3 where GUI design is introduced. The user is requested to choose options from the GUI once he starts the experiment. After starting, the software will handle the arm posture replication by incorporating the IMUs and the vibrotactile feeback. Based on the chosen option from beginning, the visual feedback should be provided. First of all, the program extracted the master's IMU information from database, using the kinematic formulation for arm model to evaluate the target positions of the wrist, the elbow and the forearm's roll. The continuous loop achieved the real time data from the student's IMU, elevating in the same way with the master to find the current positions of the wrist, the elbow and the forearm's roll. Secondly, the software compares the target and current positions to determine vibrotactile feedback that will be sent wirelessly to the tactor set in student's arm. The vibration pattern and strategy for tactor operation are depended on what option the user had chosen at beginning; they are described in chapters 4 and 5 corresponding to different sets of experiments. Thirdly, after sending the vibrotactile feedback signal, the student is required to adjust the current arm posture. The loop continues executing until the arm posture target is achieved. All the data include: the orientation, the angular velocity, the angular acceleration of IMU; the position, the linear velocity, the linear acceleration of the wrist, the elbow; the error for 3 parameters (wrist position, elbow position, forearm's roll) are recorded along the replication process.

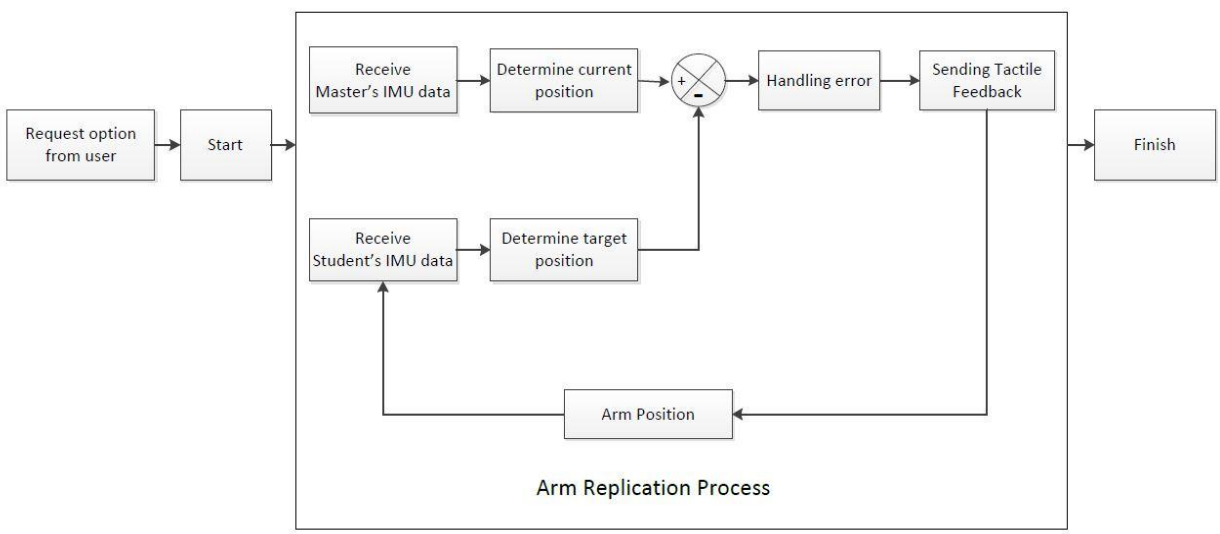


Figure 3- 5: System overview of software development

3.4.2 Platform for system design

In order to develop a GUI with number of advanced function, the QT framework is utilized in this research. The reason is that cross-platform application framework that is widely used for developing application software with GUI (in which cases Qt is classified as a *widget toolkit*), and also used for developing non-GUI programs such as command-line tools and consoles for servers.

Qt is developed by an open source project, the Qt Project, involving both individual developers as well as developers from Nokia, Digia, and other companies interested in the development of Qt. Prior to the launch of the Qt Project, it was produced by Nokia's Qt Development Frameworks division, which came into being after Nokia's acquisition of the Norwegian company Trolltech, the original producer of Qt.

Qt uses standard C++ but makes extensive use of a special code generator (called the *Meta Object Compiler*, or *moc*) together with several macros to enrich the language. Qt can also be used in several other programming languages via language bindings. It runs on the major desktop platforms and some of the mobile platforms. It has extensive internationalization support. Non-GUI features include SQL database access, XML parsing, thread management, network support, and a unified cross-platform API for file handling.

Distributed under the terms of the GNU Lesser General Public License (among others), Qt is free and open source software. All editions support a wide range of compilers, including the GCC C++ compiler and the Visual Studio suite.

Qt works on the following platforms:

- Windows – Qt for Microsoft Windows
- Windows CE / Mobile – Qt for Windows CE/Windows Mobile
- Symbian – Qt for the Symbian platform. Qt is to replace Nokia's Avkon as the supported UI SDK for the development of Symbian applications.[38] The Qt for Symbian development group has many quality-controlled articles available.
- Mac OS X – Qt for Apple Mac OS X. Support for applications on top of Cocoa APIs
- X11 – Qt for X Window System (GNU/Linux, FreeBSD, HP-UX, Solaris, AIX, etc.)
- Embedded Linux – Qt for embedded platforms (PDA, Smartphone, etc.)
- Maemo/MeeGo – Qt for Maemo, merged with Moblin to MeeGo. There are many applications already written for Maemo based on the previous Internet tablets. The Nokia

N900 also supports Qt. The Forum Nokia Wiki has quality-controlled articles that support Qt development. The Maemo operating system has a development group on the Forum Nokia Wiki at Forum Nokia Wiki Maemo.

- Wayland – Qt for Wayland display server. Qt applications can switch between graphical backends like X and Wayland at run time with the -platform command line option.

The feature of QT framework is really nice and user-friendly, shown in Fig.3-6. There are four main sections in QT window:

1. Project manager: list of header, C , GUI design and resource files of whole project
2. Programming window: for editing and writing the code
3. Application Output: debugging process
4. Open Documents: to highlight what files we are handling

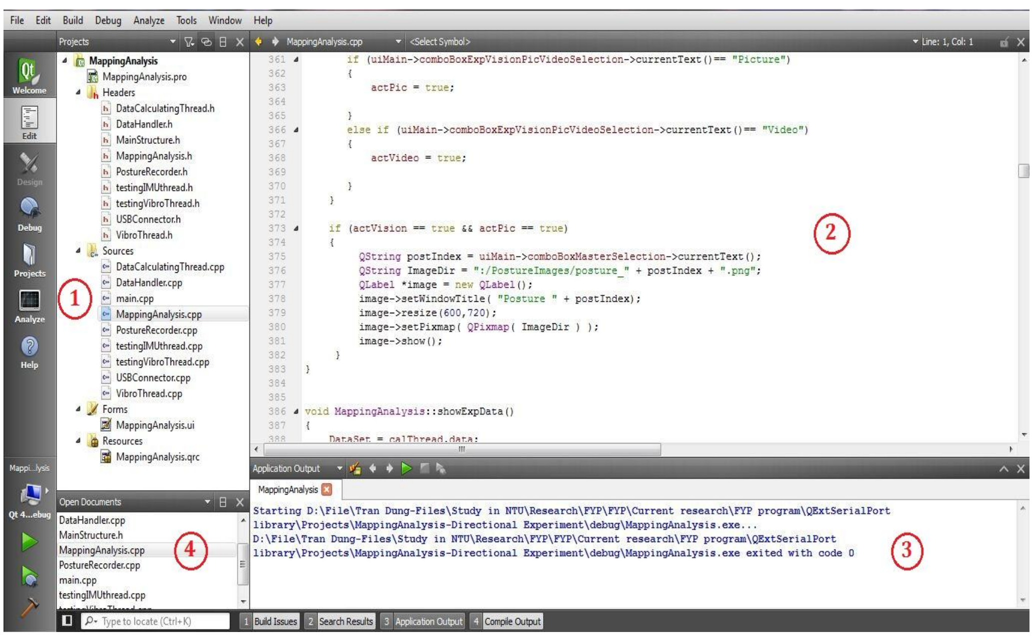


Figure 3- 6: QT framework interface

3.4.3 Design for GUI

The developed software with GUI contains 3 tabs: configuration, testing and experiment. The detail function for each tab will be elaborated more in following parts.

a. Configuration setting Tab

This tab lets the user record setting parameters before handing experiment. As shown in Fig.3-7, the setting parameters include: the subject's arm lengths (the upper arm and the forearm) (label 1), threshold values (allowable errors for mapping 3 parameters: the wrist position, the elbow position and the forearm's roll) (label 2).

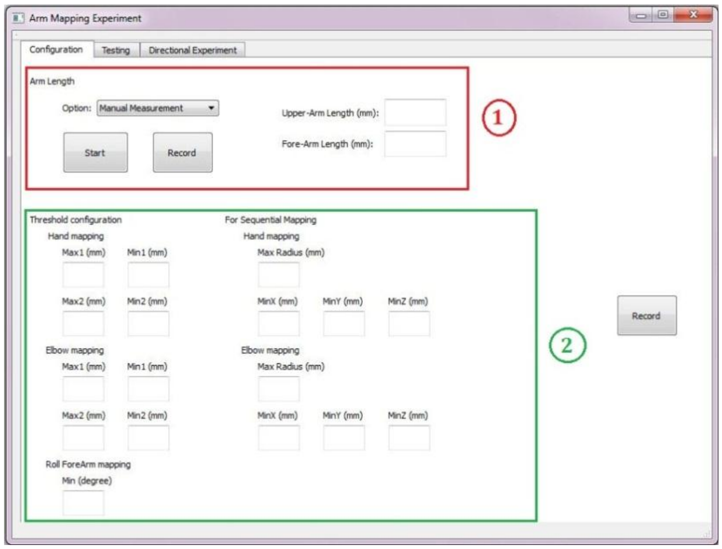


Figure 3- 7: Configuration setting tab of developed software

b. Testing Tab

Testing tab provides the testing function for the IMU and the vibrotactor. It helps determining if the IMU or the vibrotactor is connected properly with the system. With IMU testing function, the recording for reference posture is incorporated in this tab. Moreovers, the testing of vibrotactor provides the training to the subject, the magnitude or vibration pattern can be set easily, to make the subject familiar with the system. Details of tab feature are shown in Fig.3-8 with 3 main sections:

1. Testing values received from IMUs before experiment
2. Saving current Arm posture as Master posture for reference
3. Testing the Bluetooth connection between software and tactors

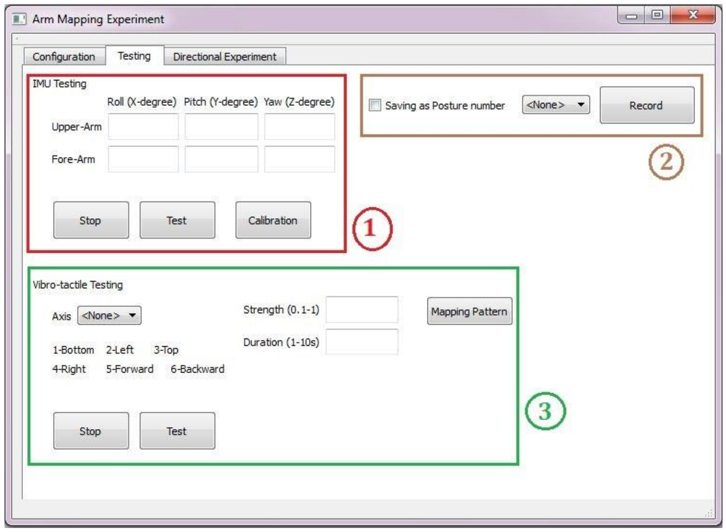


Figure 3- 8: Testing tab of developed software

c. Experiment Tab

After testing with devices (the IMU and the vibrotactor) and inserting all necessary setting parameters (arm lengths, thresholds), the experiment will be conducted separately in Experiment Tab. The experiment can be handled easily by choosing which kind of experiment (using vibrotactile feedback as direction or error matching indicator, whether the visual feedback is involved), posture number and subject number. The real time IMU data, the wrist position, the elbow position, the matching error are recorded and saved into a single text file for data handling after experiment. The final errors for the wrist position, the elbow position, the forearm's roll and the mapping time are recorded once the posture replication is finished. Detail of the tab is shown in Fig.3-9 with the following description:

1. Number of loops for finding the wrist and elbow positions.
2. Select the posture number that you want to replicate.
3. Select the candidate number and do calibration before experiment.
4. Choose visual and tactile feedback combination, it is used for the "Investigation of different combination of visual and vibrotactile feedback" that is discussed in Chapter 5.
5. Option for directional vibrotactile feedback, it is used for the "Investigation of using vibrotactile feedback as direction or matching error indicators" that is discussed in Chapter 4.
6. Shows the IMU data from Master's posture and Student's posture.

7. Shows the real time coordinate of the wrist and elbow positions as well as the real time error during the whole replication process.
8. Immediate stop and record function of the software.

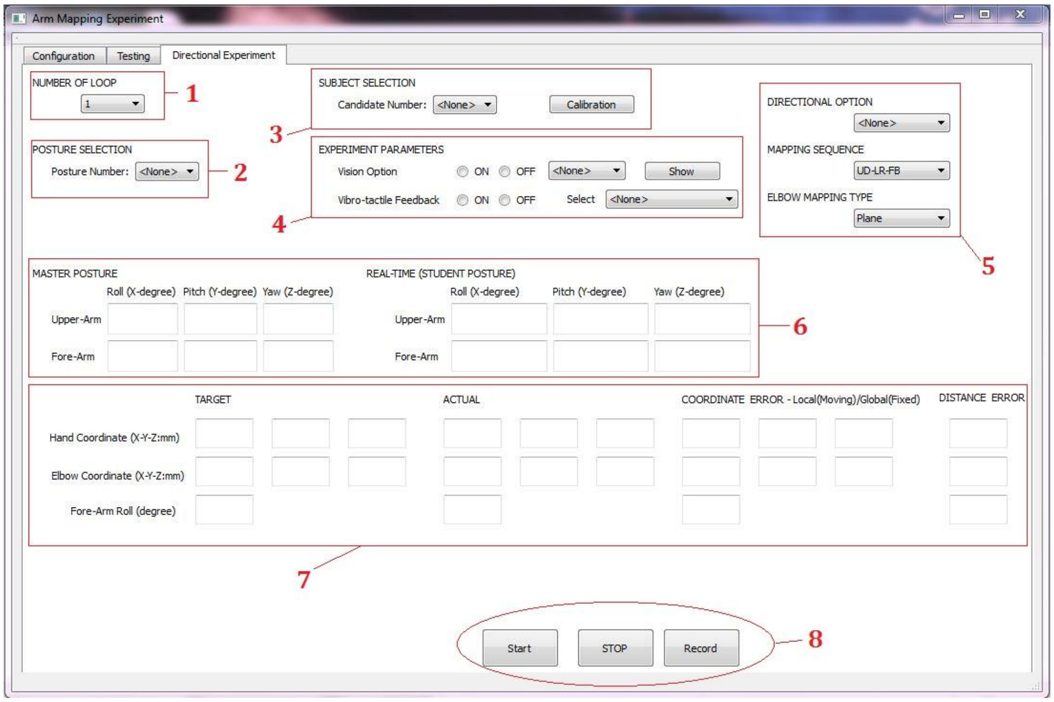


Figure 3- 9: Experiment tab of developed software

3.4.4 Structure of developed source code

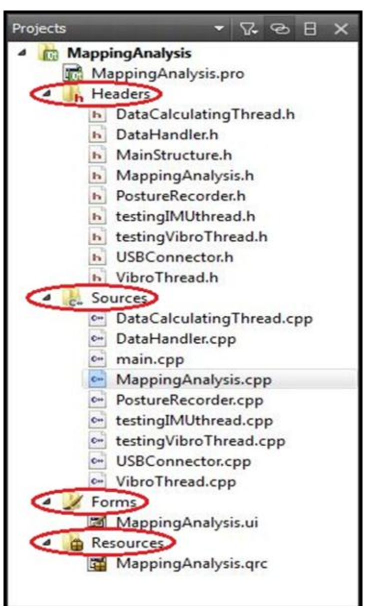


Figure 3- 10: Structure of source code

The programming files are organized based on 4 categories: (Fig.3-10)

- Header files
- Source files
- Forms: GUI design for software with 2 separating area as shown in Fig.3-11.
- Resources: managing all resources of software such as posture video, posture image, text file for data recording…

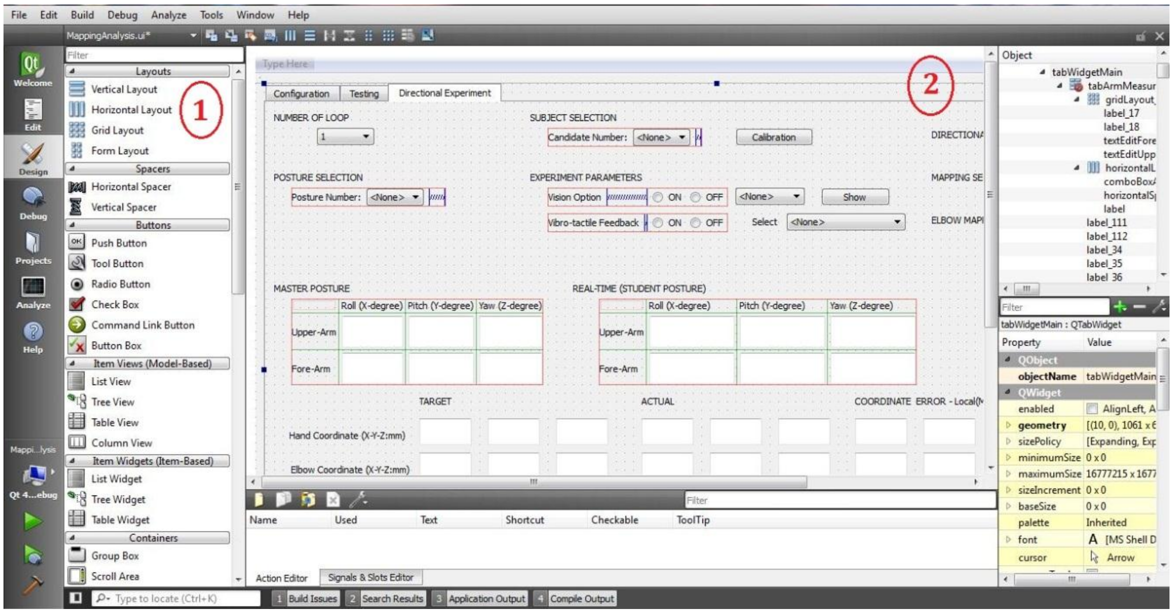


Figure 3- 11: Creating design for developed software

Chapter 4: Investigation of Using Vibrotactile Feedback as Direction or Matching Error Indicators

4.1 Introduction

In designing a system for arm posture replication, it consists of two processes: motion captures and motion indicators (motion feedback). For the feedback, we can employ audio feedback, visual feedback or tactile feedback. In this project, the main focus is the usage of vibrotactile feedback as motion indicators. It can be used as indicator for directional feedback or matching error.

- By using vibrotactile feedback as directional indicator, a set of six tactors are designed to indicate the 6 moving directions in 3D space as shown in Fig.4-1. The set of tactors can be either worn on the moving arm or the stationary arm.
- By using vibrotactile feedback as matching error indicators, the user will obtain the signal from vibrotactile feedback to recognize the error magnitude determined by the distance between the current and the target positions.

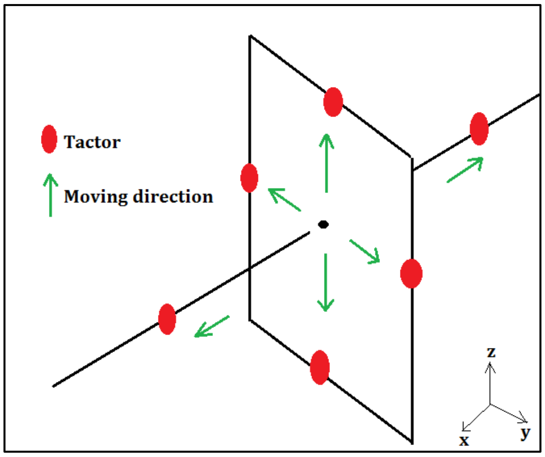


Figure 4- 1: Six moving directions in 3D space

The summary of different feedback modes is illustrated in Fig.4-2.

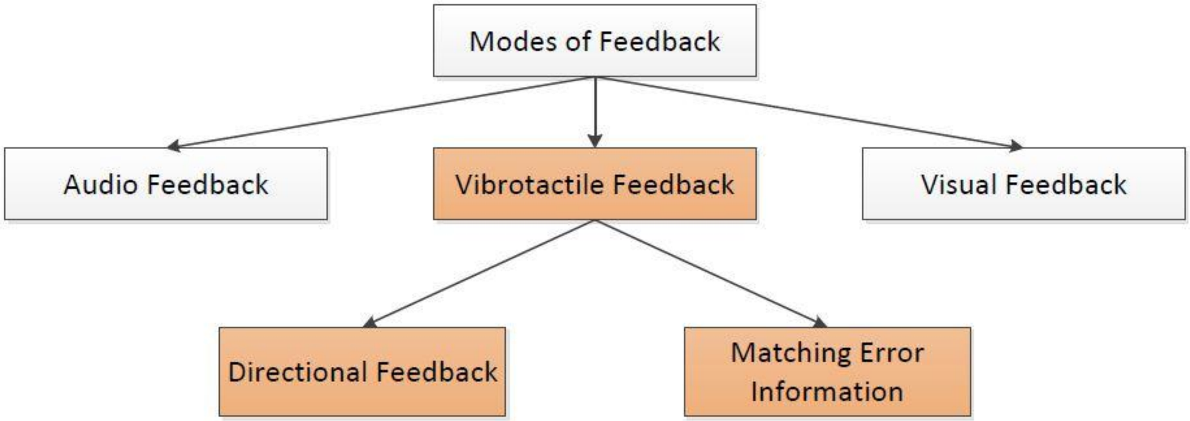


Figure 4- 2: Different usage of vibrotactile feedback

4.2 Feedback strategy

Two feedback strategies are proposed in this section. In the first strategy, vibrotactile feedback provides matching error information to the user in replicating an arm posture. The user has to interpret the feedback given by the tactors and determine where to move his arm with respect to the error detected by the system. Second is to use vibrotactile feedback to provide directional information. That is, the feedback will directly inform the user where to move his arm with respect to the error detected by the system. Two different vibration patterns are used for the different strategies as illustrated in Fig.4-3: (a) for providing matching error and (b) for directional vibrotactile feedback. There are 3 different phases for each type of the feedback. Table 4-1 lists different phases for each vibration pattern.

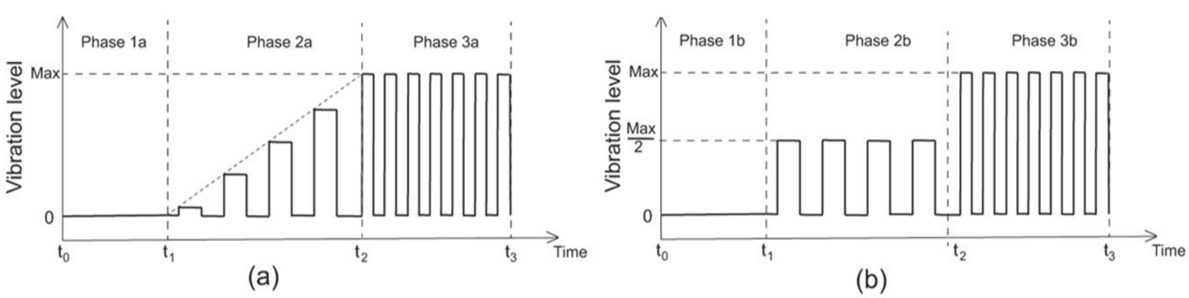


Figure 4- 3: Vibration pattern for providing: (a) matching error and (b) directional feedback

Table 4- 1: Three phases of vibration pattern

Phase	Providing matching error (a)	Directional Vibrotactile Feedback (b)
1	No vibration	No vibration
2	Vibration at a constant frequency (100Hz) where magnitude is inversely proportional to error	Vibration at a constant frequency (100Hz) where magnitude is half of maximum magnitude
3	Vibration at a constant frequency (200Hz) at maximum magnitude	Vibration at a constant frequency (200Hz) at maximum magnitude

4.2.1 Vibrotactile motors on moving arm as directional feedback

The protocol for arm posture replication starts with correcting the wrist position. Six tactors are located at different locations of forearm as shown in Fig.4-4 and the vibrotactile unit is worn on the arm as shown in Fig.4-5. Assuming a sphere with radius $R_{D\_OUTER\_W}$ is concentric with the target wrist position. If the wrist is outside of the sphere, there will be no vibration Phase 1b. Once the wrist is inside of the sphere, one of the z tactors (z_1 or z_2) and the y tactors (y_1 or y_2) vibrate (i.e., Phase 2b) to guide the user in moving his wrist along z-axis and y-axis. Four tactors (z_1, z_2, y_1, y_2) vibrate continuously at Phase 3b when the errors along the z and y axes are smaller than $T_{D\_INNER\_W}$. Then either x_1 or x_2 tactor will continue vibrating at Phase 2b to guide the wrist to move along the x-axis until the x-axis error is smaller than $T_{D\_INNER\_W}$ wherein the two tactors x_1 and x_2 vibrate continuously at Phase 3b. Finally, all six tactors vibrate at Phase 3b to tell the user that correction of wrist position is finished.

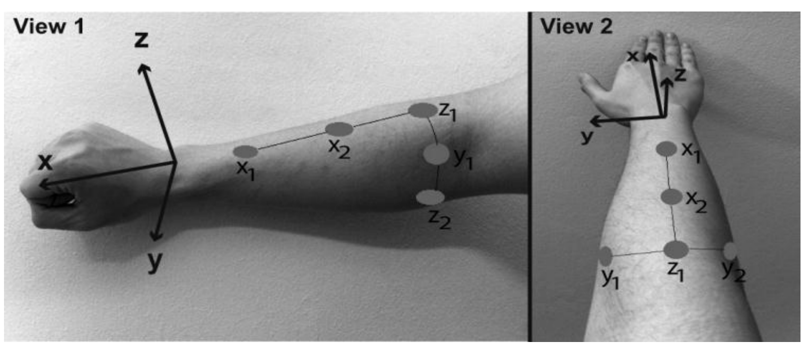


Figure 4- 4: Approximate location of the vibrotactile actuators (tactors) on the right arm

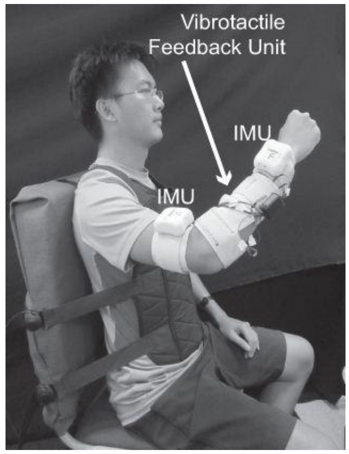


Figure 4- 5: The experiment setup - Vibrotactile motors on moving arm as directional feedback

The next parameter to correct is the elbow position. For the elbow position correction, the reference position is computed to determine whether it lies above or below the arm plane determined by the wrist, the elbow and the shoulder. The threshold for the elbow correction is defined as a sphere with radius R_{INNER_E} and concentric with the target elbow position. Any two tactors z_1 or z_2 together with y_1 or y_2 will vibrate at Phase 2b to indicate which direction the elbow should move. Phase 3b occurs when the elbow is within the threshold sphere.

Finally, for the correction of the forearm roll, the permissible range of deviation is defined to be $\Delta\varphi_f$. One of tactors on the side (y tactor) starts vibrating in Phase 2b to indicate the rotation direction. Once the fore-arm's roll is within the $\Delta\varphi_f$ threshold, the tactors vibrate as in Phase 3b.

4.2.2 Vibrotactile motors on stationary arm as directional feedback

Six tactors are located at different locations of the left forearm as shown in Fig.4-6 and the vibrotactile unit is worn on the stationary arm as shown in Fig.4-7. Each axis is assigned two tactors to provide the user directional information in 3D space. Assuming a sphere with radius $R_{D\_OUTER\_W}$ is concentric the target wrist position, if the wrist is still outside the sphere, Phase 1 occurs, i.e., no vibration. Once the wrist is within the sphere, one of the z (z_1 or z_2) vibrates with Phase 2 pattern to guide the user to move his wrist along the z axis. The two tactors (z_1, z_2) simultaneously vibrate at Phase 3 pattern when the error along the z axis is smaller than $T_{D\_INNER\_W}$). The vibration pattern is repeated for moving guidance in the y and x axes subsequently. To signal the end of correction for wrist position, all six tactors will activate at Phase 3 pattern.

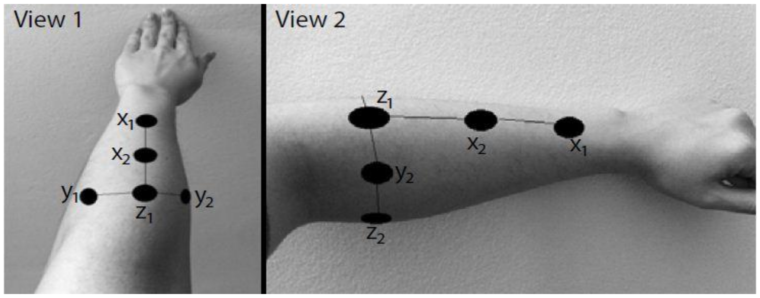


Figure 4- 6: The approximate location of the tactors on the left forearm (top and side views)

The next parameter to be corrected is the elbow position. The elbow's reference position is determined whether it lies above or below the plane determined by the wrist, the elbow and the shoulder. One of the z (z_1 or z_2) and one of the y tactors (y_1 or y_2) vibrate together with Phase 2 pattern to guide the user to correct the elbow position. Then Phase 3 takes place when the elbow is within the specified threshold. The threshold for the elbow correction is a sphere with radius R_{INNER_E}, and concentric with the target elbow position.

Finally, in the forearm roll correction, the permissible range of deviation is $\Delta\varphi_f$. One of the y tactors starts vibrating with Phase 2 pattern to indicate which direction to rotate the forearm. Once the forearm roll is within the $\Delta\varphi_f$ threshold, the tactor vibrates as Phase 3.

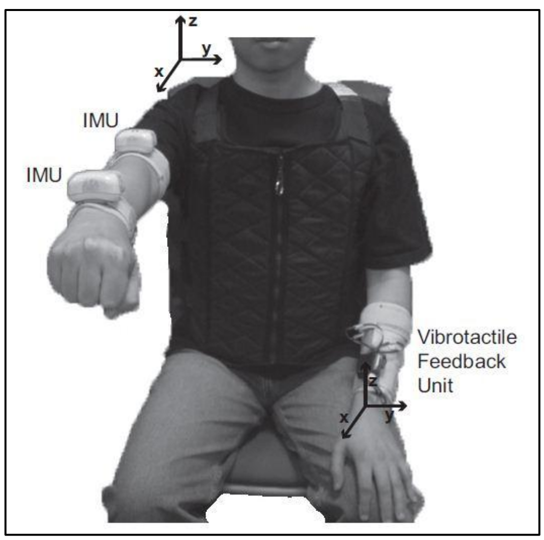


Figure 4- 7: The user wears the IMUs on the right hand and the vibrotactile feedback unit on the left

4.2.3 Vibrotactile feedback as providing matching error information:

The placement for vibrotactile unit for using vibrotactile feedback as providing matching error information is shown in Fig.4-8. The protocol for arm posture replication starts with correcting the wrist position. The thresholds are defined by two spheres with radii of $R_{ND\_OUTER\_W}$ and $R_{ND\_INNER\_W}$. Both spheres are concentric with the target wrist position. During Phase 1a vibrotactile feedback is absent since the wrist position is outside of the sphere with radius $R_{ND\_OUTER\_W}$. Once the wrist is within the range of [$R_{ND\_INNER\_W}$, $R_{ND\_OUTER\_W}$], Phase 2a begins. Finally, when the wrist position is within the permissible deviation (i.e., the wrist is within the sphere with radius $R_{ND\_INNER\_W}$), the vibration magnitude is set to maximum and the vibrotactile motor vibrates continuously (Phase 3a).

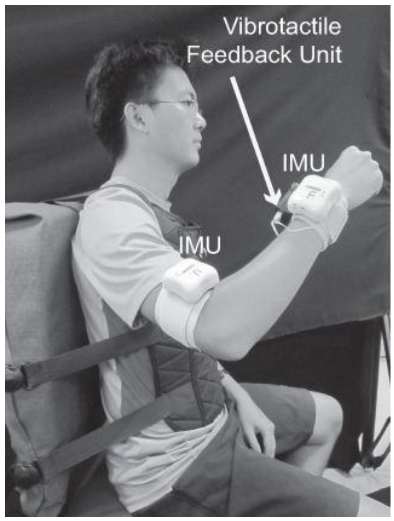


Figure 4- 8: The experiment setup: Vibrotactile motors on moving arm as providing matching error

The next parameter to correct is the elbow position. For the elbow position correction, the reference position is computed to determine whether it lies above or below the arm plane determined by the wrist, the elbow and the shoulder. The threshold for the elbow correction is defined as a sphere with radius R_{INNER_E} and concentric with the target elbow position. Vibrotactile feedback is absent as long as the elbow is moving in wrong direction, ie, opposite the location of the reference position w.r.t. the arm plane. Phase 2a begins when the elbow moves to the correct direction. Correction enters Phase 3a when the location of the elbow falls within the threshold sphere.

Finally, for the correction of the forearm roll, the permissible range of deviation is defined to be $\Delta\varphi_f$. Phase 1a is when the forearm rotates to the opposite direction (clockwise or counter-clockwise) as the reference angle. As soon as the forearm moves to the right direction, Phase 2a begins. When the forearm roll angle is within the $\Delta\varphi_f$ threshold, Phase 3a starts.

4.3 Experimental investigations

4.3.1 Subjects

Student volunteers from the university, with ages from 20-25 years, participated in the experiments. All are healthy and without any medical condition that could have affected their tactile sensitivity.

4.3.2 Reference postures

Five postures are selected as reference for the experiments (see Fig.4-9). The postures are at the anterior (postures 1, 2, 3) and posterior (postures 4, 5) of the body. Postures 1 to 3 are quite easy to do, while postures 4 and 5 could be challenging since they are unnatural. Postures 2 and 4 take some effort to do as it is tiring to keep up the arm.

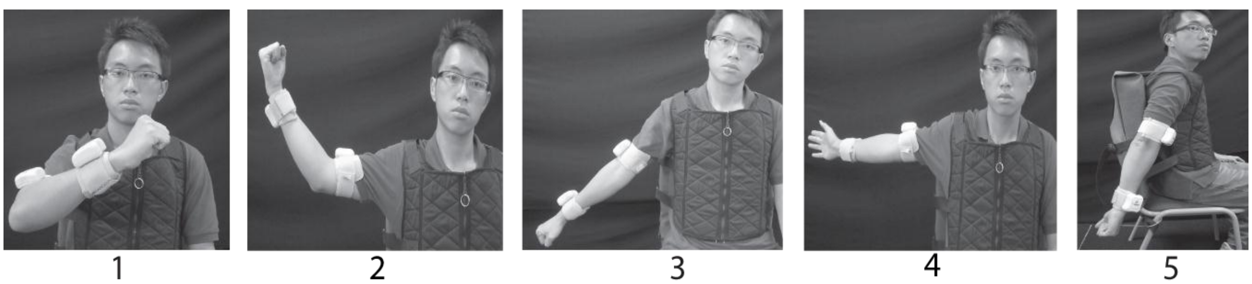
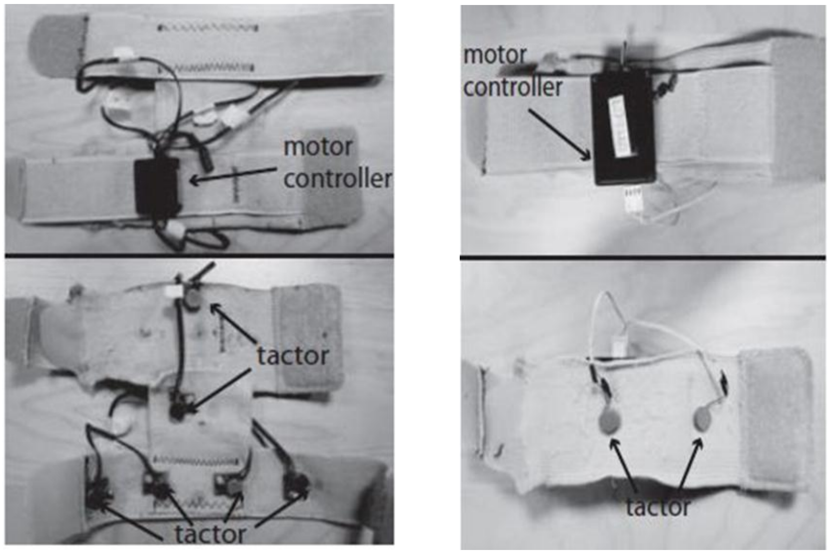


Figure 4- 9: Five reference postures

4.3.3 Hardware setup

Two IMUs are placed on the user's right arm (moving arm), one is near the elbow and the other is near the wrist. The vibrotactile motors are mounted on the underside of an elastic arm band. The digital controller is inside the black box mounted on the top side of the arm band. The IMUs connect to the computer via a 2.4GHz wireless system and the vibrotactile feedback unit via Bluetooth.



(a) (b)

Figure 4- 10: Vibrotactile feedback unit: (a) directional vibrotactile feedback, (b) providing matching error

For using vibrotactile motors as directional feedback, the vibrotactile unit is shown in Fig.4-10(a). A total of six tactors are used: four tactors are placed around the subject's forearm symmetrically and two more tactors along the forearm. it is worn either in moving arm for "Vibrotactile motors on moving arm as directional feedback" approach (Fig.4-5) or in stationary arm for "Vibrotactile motors on stationary arm as directional feedback" approach (Fig.4-7).

For using vibrotactile motors as providing matching error information, the vibrotactile unit is shown in Fig.4-10(b). There are two tactors used and placed on two sides of the wrist on moving arm (Fig.4-8).

4.3.4 Experiment procedure

During the student is strapped to a chair to minimize shoulder movement; two IMUs are attached to the forearm and the upper arm. A set of vibrotactile feedback unit (2 tactors for using tactor as matching error information experiment (Fig.4-8) and 6 tactors for direction experiment on either moving arm (Fig.4-5) or stationary arm (Fig.4-7)) is attached to the forearm.

The experiments require a master, who establishes the reference posture, and students, who must copy the reference posture. The students must replicate all five postures in Fig.4-9 selected in random order. For each experiment, whether using tactor as providing matching error information or directional feedback, the following procedures are followed:

1) The master wears two IMUs and assumes the reference posture.

2) A student wears two IMUs and one vibrotactile unit.

3) The student stretches out his arm in front to calibrate the IMU coordinate system.

4) The student assumes the starting position: arms on the side.

5) The student starts correcting arm posture with respect to the randomly selected reference.

For using tactor as matching error information experiment:

a) The student starts correcting his wrist position. If the tactor is not vibrating, it means that he is far from the target or moving (for elbow) or rotating (for forearm) to the wrong direction (Phase 1a).

b) Once the wrist comes within the set threshold (or correct direction, in the case of the elbow and forearm), the tactors would vibrate at 100Hz. The magnitude of vibration is inversely proportional to the distance from the reference position (Phase 2a).

c) The student must continue moving his arm in the current direction of motion until the vibration pattern changes to a higher frequency (200 Hz) and highest magnitude (Phase 3a).

d) Steps 5a to 5c are repeated for the next posture parameter until all parameters are exhausted.

For direction experiment:

a) The student starts correcting his wrist position (w.r.t. x, y and z axes of the arm coordinate system). If the tactor is not vibrating, it means that the wrist is far from the target (Phase 1b).

b) Once the wrist is within the set threshold, one of the tactors will vibrate at 100Hz and half of maximum vibrating magnitude (Phase 2b) to guide the user which direction to move (either y and z directions).

c) The student must continue moving his wrist in the current direction of motion until the vibration pattern changes to a higher frequency (200 Hz) and highest magnitude (Phase 3b). Correction in the y and z axes is done.

d) Steps 5b to 5c are repeated for the x axis.

e) After the wrist position is corrected, the student starts adjusting the elbow position and fore arm's roll by following the direction provided by the tactors from Phase 2b until Phase 3b.

For comparison of the subject's performance, the master's posture is recorded first and just loaded up at the beginning of each experiment. The set of threshold values for using vibrotactile motors as providing matching error information and directional feedback are listed in Table 4-2.

Table 4- 2: Threshold values for the arm posture parameters

Parameter	Threshold Values
Wrist (Providing error information) : $R_{ND\_OUTER\_W}$	200 mm
Wrist (Providing error information) : $R_{ND\_INNER\_W}$	25 mm
Wrist (Direction) : $R_{D\_OUTER\_W}$	300 mm
Wrist (Direction) : $T_{D\_INNER\_W}$	15 mm
Elbow : R_{INNER_E}	25 mm
Forearm : $\Delta\varphi_f$	10^o

4.4 Results and discussion

4.4.1 Comparison between the usage of tactors as direction and matching error indicators

We compared the performance of using the two vibrotactile feedback strategies in correcting the arm posture by evaluating the total mapping time (how long it takes to replicate a posture) and accuracy (w.r.t to each parameter of the reference posture).

a. Mapping time

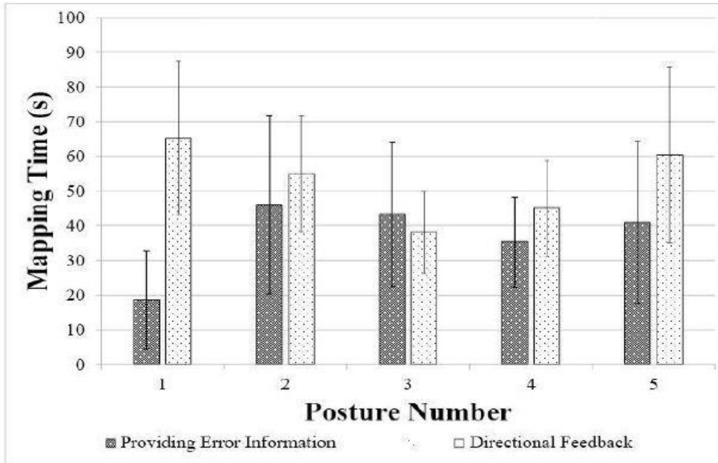


Figure 4- 11: Average Mapping time of 7 subjects for 5 postures

Figure 4-11 shows the graph of the average mapping time of seven subjects for five postures and two different vibrotactile feedbacks. The mapping time is slightly different between the two feedback modes as well as among five postures. Overall, the usage of vibrotactile feedback as providing error information allowed faster arm posture replication (36.82 s) compared to the directional feedback (52.68 s) as listed in Table 4-3. The more complex (posture 1) and the more unnatural (posture 5) is the posture, the shorter is the mapping time for the usage of vibrotactile feedback as providing error information.

Table 4- 3: Average mapping time of 7 subjects for the 5 postures

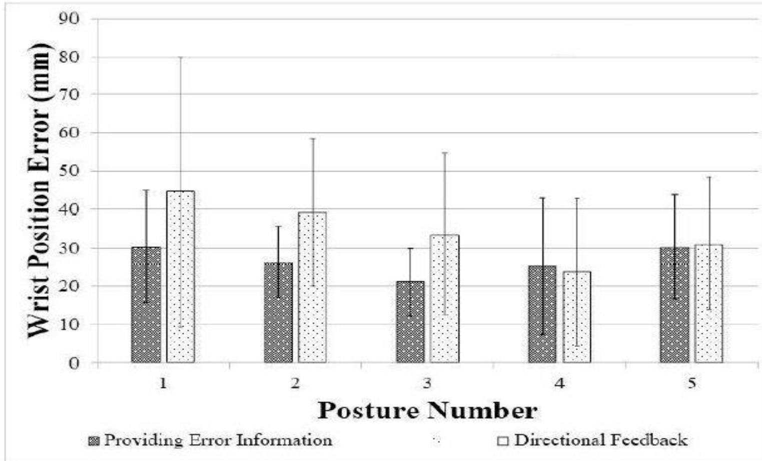
Feedback Strategy	Mapping Time (s)
Providing error information	36.82 ± 19.37
Directional feedback	52.68 ± 17.98

b. Mapping accuracy

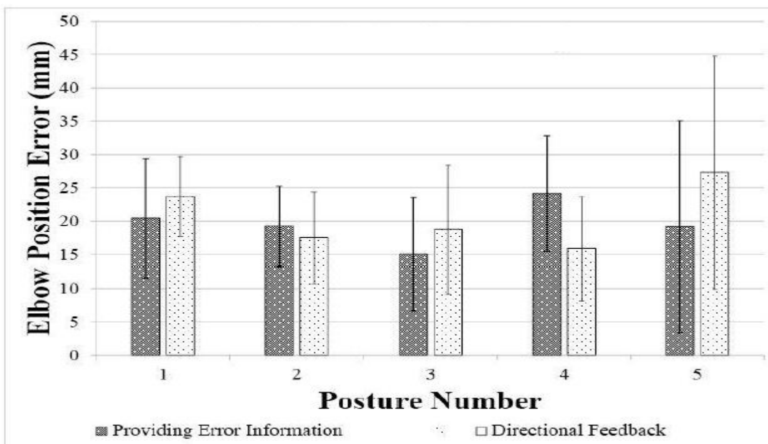
The accuracy of the two feedback strategies is evaluated through three parameters: wrist position, elbow position and forearm’s roll. The average error for the five postures among the seven students is listed in Table 4-4. As the strategy for correcting the elbow and the forearm is the same for both feedback strategies, the error is also similar.

Table 4- 4: Average error of seven subjects for the five postures

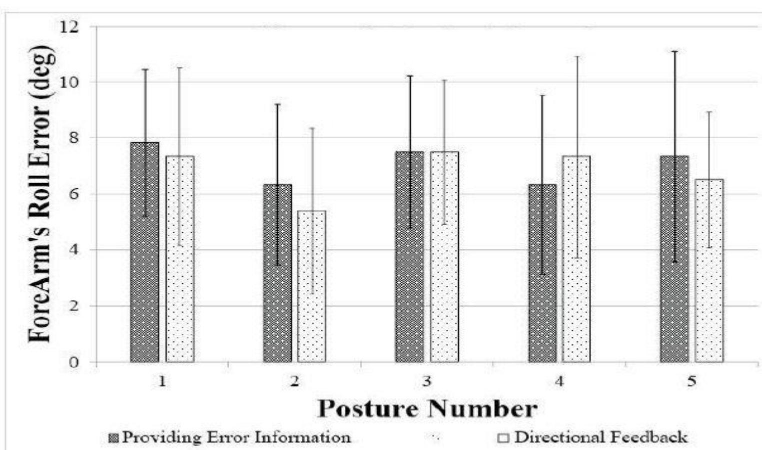
Error	Providing matching error	Directional feedback
Wrist position (mm)	26.61 ± 12.92	34.42 ± 22.46
Elbow position (mm)	19.61 ± 9.56	20.63 ± 9.53
Forearm roll (deg)	7.07 ± 3.05	6.81 ± 2.96



(a) Wrist position error



(b) Elbow position error



(c) Forearm's roll error

Figure 4- 12: Average mapping errors of using vibrotactile feedback as direction and matching error indicators

On the other hand, the usage of vibrotactile feedback as providing error information provides smaller wrist position's error. This is due to the mapping process of wrist position in directional strategy. The process is broken down into sub-steps where correction happens for every axis sequentially as compared to the simultaneous 3D position correction for the usage of vibrotactile feedback as providing error information strategy. The average errors of seven subjects for each posture are represented in details in Fig.4-12.

c. Conclusion

Based on the results, the usage of vibrotactile feedback as providing error information may be viewed as better feedback mode in arm posture replication. It provided both shorter mapping time (~16s) and higher accuracy in arm posture replication (~8mm for wrist position).

4.3.2. Comparison of directional vibrotactile feedback on the moving arm and on the stationary arm

To verify the feasibility of the arm posture correction system, we compared the correction time and the accuracy for five different postures.

a. Mapping time

There are some interesting points when we compared the performance of using vibrotactile tactors as directional feedback either on stationary arm or moving arm. Table 4-5 shows the average mapping time of seven subjects for the five postures with 2 different directional feedback approaches, either on stationary or moving arm. The directional feedback on stationary arm took 46.80 seconds in average to complete the posture correction; it is less than the directional feedback on moving arm that required 52.68 seconds. It is reasonable while the directional feedback made some confused for the users during whole arm mapping process. As results, it took longer time to complete the mapping.

Table 4- 5: Average mapping time of time of directional feedback strategies

Feedback Strategy	Mapping Time (s)
Directional Feedback on Stationary Arm	46.80 ± 13.23
Directional Feedback on Moving Arm	52.68 ± 17.98

When investigating each individual posture, there is no much difference in mapping time among postures 2, 3, 4 (those simple postures). However, the directional feedback on stationary arm provided shorter mapping time for posture 1 (complex posture) and posture 5 (required more efforts to complete, tiring posture) (see Fig.4-13).

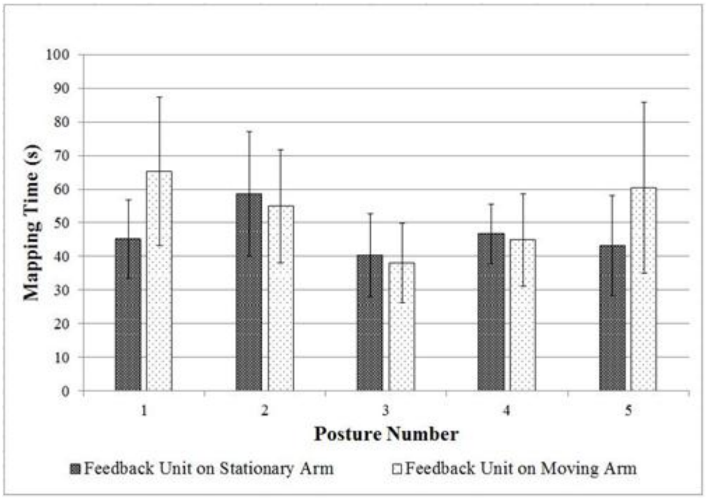


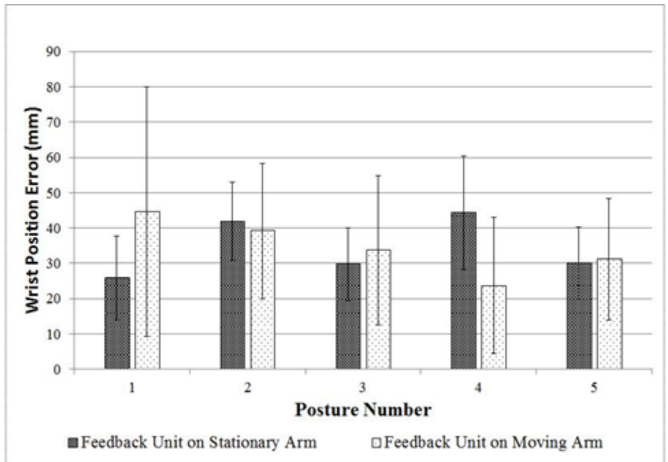
Figure 4- 13: Average mapping time of directional feedback strategies

b. Mapping accuracy

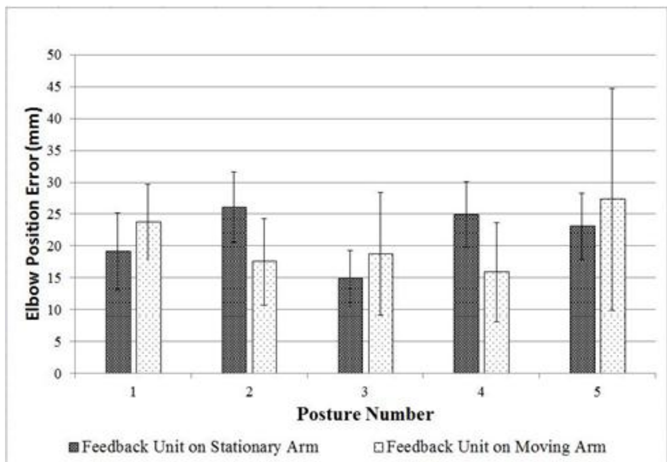
Based on Table 4-6, the average error of seven subjects for the five postures with two different directional feedback approaches are compared. For directional vibrotactile feedback either on stationary arm or moving arm, the wrist position, elbow position as well as forearm roll error are not much different between two approaches. The detailed information for each individual posture is presented in Fig.4-14.

Table 4- 6: Average mapping error of directional feedback strategies

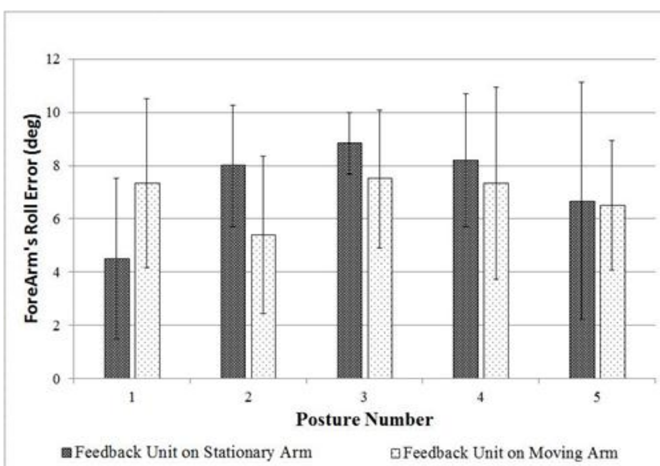
Error	Directional Feedback on Stationary Arm	Directional Feedback on Moving Arm
Wrist position (mm)	34.35 ± 11.93	34.42 ± 22.46
Elbow position (mm)	21.61 ± 5.28	20.63 ± 9.53
Forearm roll (deg)	7.24 ± 2.68	6.81 ± 2.96



(a) Wrist position error



(b) Elbow position error



(c) Forearm's roll error

Figure 4- 14: Average mapping errors of two directional feedback strategies

c. Conclusion

Overall, the directional feedback on stationary arm provides faster mapping time to complete the posture correction (~6s). However, the mapping errors between two approaches, either on stationary or moving arm are comparable. Therefore, the directional feedback on stationary arm is the preferred strategy.

Chapter 5: Investigation of Different Combinations of Visual and Vibrotactile Feedback

The use of vibrotactile feedback as matching error indicator provides shorter mapping time and relatively better matching accuracy compared to using it as direction indicator. This chapter presents the effect of incorporating visual cue with vibrotactile feedback for arm posture replication. The four feedback modes covered in research are: Visual Cue only, Vibrotactile only, Visual Cue and Vibrotactile in series, Visual Cue and Vibrotactile in parallel. The Vibrotactile feedback is used as indicator of matching error information, non-directional feedback. The performance is evaluated based on mapping time (time to complete replicating one posture) and the accuracy in term of wrist position, elbow position and forearm's roll).

5.1 Feedback modes for posture correction

Two feedback modes are used to guide the posture correction process: visual cue and vibrotactile. For visual cue, the user is shown a picture with the front view and side view of the reference posture. The picture can be shown either at the beginning or through the whole process. (see Fig.5-1).

Figure 5- 1: A visual cue used as a feedback mode

The vibrotactile feedback is used as non-directional indicator, to provide matching error information to the user. The vibration pattern as well as vibrotactile feedback strategy have been shown in chapter 4, under section 4.2.3.

The combination of vibrotactile feedback and visual feedback forms visuotactile feedback. Four different feedback strategies are implemented using the two feedback modes.

a. **Visual cue only [V]** - Only visual cue is used to correct arm posture. Correction stops when the user thinks he has achieved the reference posture.
b. **Vibrotactile only [T]** - Only vibrotactile feedback is used to correct arm posture.
c. **Visual cue and vibrotactile in series [V+T(s)]** – Vibrotactile feedback is used after visual cue. At first, the user sees the target posture (visual cue) for a fixed period of time (4s). Afterwards, visual cue is turned off and vibrotactile feedback is turned on. The user relies on vibrotactile to finish the posture correction.
d. **Visual cue and vibrotactile in parallel [V+T(p)]** – Visual cue is never turned off for the duration of the posture correction process. Thus, the subject can see the reference posture at all times.

5.2 Experimental investigations

5.2.1 Subjects

Student volunteers from the university, with ages from 20-25 years, participated in the experiments. All are healthy and without any medical condition that could have affected their tactile sensitivity.

5.2.2 Hardware setup

Two IMUs were placed on the subject's arm, one near the elbow and one near the wrist. For the vibrotactile feedback two tactors were placed around the subject's wrist, one on each side. The distance between the two tactors was larger than the two-point discrimination threshold for both male and female [33]. The tactors, secured in a holder, were attached to the underside of elastic bands to fit the arm of different subjects. Fig.5-2 shows the unmounted vibrotactile feedback unit. The digital controller is inside the black box. The IMUs connect to the computer via a 2.4GHz wireless system and the vibrotactile feedback unit via Bluetooth.

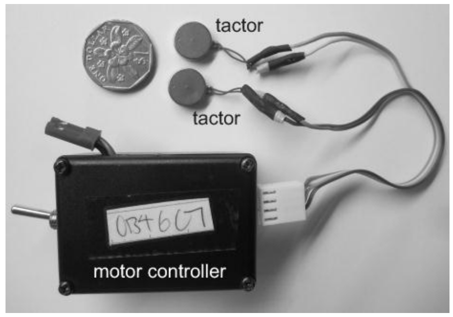


Figure 5- 2: The vibrotactile feedback unit

5.2.3 General procedure

The set-up for the experiment is illustrated in Fig.5-3. The subject, while wearing two IMUs and the vibrotactile feedback unit on the arm, is strapped to a chair to minimize shoulder movement. Visual cue is provided through the laptop in front of the user.

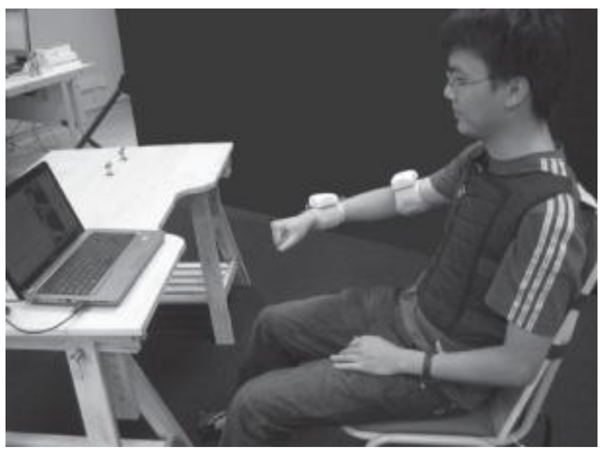


Figure 5- 3: The experiment setup

The experiments require a master, who establishes the reference posture, and students, who must copy the reference posture. For each experiment, the following procedures were followed:

1. The master wears two IMUs and assumes the reference posture.

2. A student wears two IMUs and one vibrotactile unit as shown in Fig.5-4, the tactors are mounted under the strap that holds the IMU and the motor controller at the wrist.

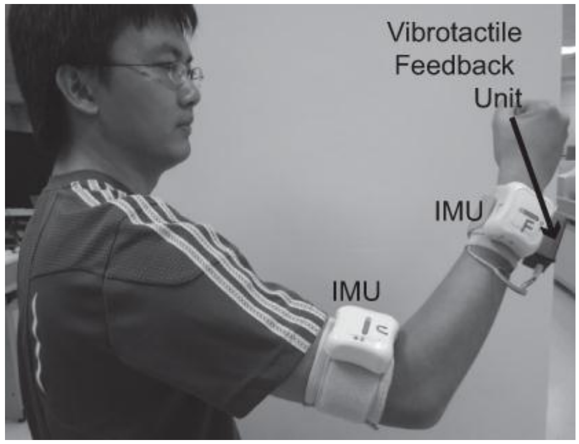


Figure 5- 4: The two IMUs and the vibrotactile feedback unit mounted on the arm of the user

3. The student stretches out his arm in front to calibrate the IMU coordinate system.

4. The student assumes the starting position: arms on the side.

5. The student starts correcting his wrist position. If the tactor is not vibrating, it means that he is far from the target or moving (for the elbow) or rotating (for the forearm) to the wrong direction (**Phase 1**).

6. Once the wrist comes within the set threshold (or correct direction, in the case of the elbow and forearm), the tactors would vibrate at 100Hz. The magnitude of vibration is inversely proportional to the distance from the reference position (**Phase 2**).

7. The student must continue moving his arm in the current direction of motion until the vibration pattern changes to a higher frequency (200 Hz) and the highest magnitude (**Phase 3**).

8. Steps 5 to 7 are repeated for the next posture parameter until all parameters are exhausted.

For comparison of subject's performance, the master's posture is recorded and just loaded up at the beginning of each experiment instead of doing Step 1 for every experiment. Although the arm was modeled as 3-parameter system, a five step correction process was implemented. After correcting the wrist and elbow positions the first time (first loop), it would be repeated again but with different threshold values (second loop). This ensures that the subjects could find the reference position during the first time and improve accuracy during the second. The forearm's roll is the fifth and last posture parameter to be corrected. The five-step correction process is illustrated in Fig.5-5(a) and the set of threshold values are listed in Table 5-1. The posture correction process is illustrated in Fig.5-5(b) in more detail.

Table 5- 1: Threshold values for the posture parameters

Parameter	Threshold Values
Wrist (1st loop): R_{OUTER_W}	150 mm
Wrist (1st loop): R_{INNER_W}	30 mm
Elbow (1st loop): R_{INNER_E}	30 mm
Wrist (2nd loop): R_{OUTER_W}	100 mm
Wrist (2nd loop): R_{INNER_W}	25 mm
Elbow (2nd loop): R_{INNER_E}	25 mm
Forearm: $\Delta\varphi_f$	10^{o}

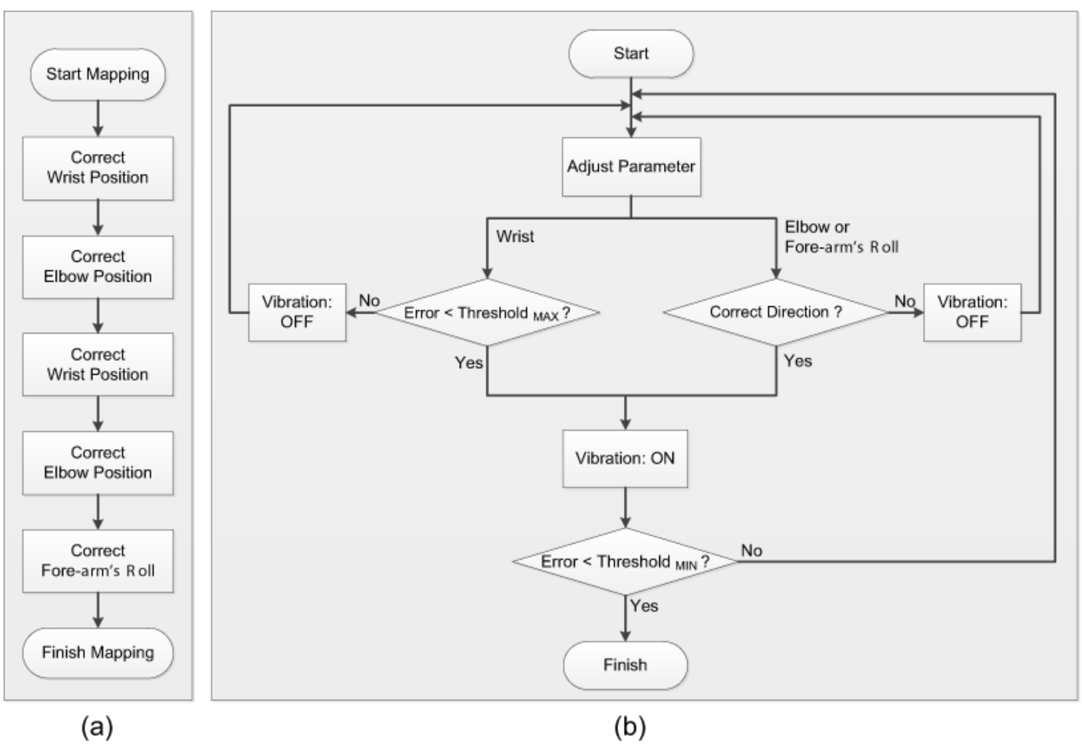


Figure 5- 5: The mapping process

5.2.4 Reference postures

Ten postures are selected as reference for the experiments and illustrated in Fig.5-6. Some of the postures are at the anterior (postures 1, 2, 3, 4, 5, 10) and posterior (postures 6, 7, 8, 9) of the body. Postures 1 to 4 are quite easy to execute, while postures 6 to 9 could be challenging due to their unnaturalness. Moreover, despite Postures 5 and 10 being simple looking, they can be challenging as well since they need extra effort to execute.

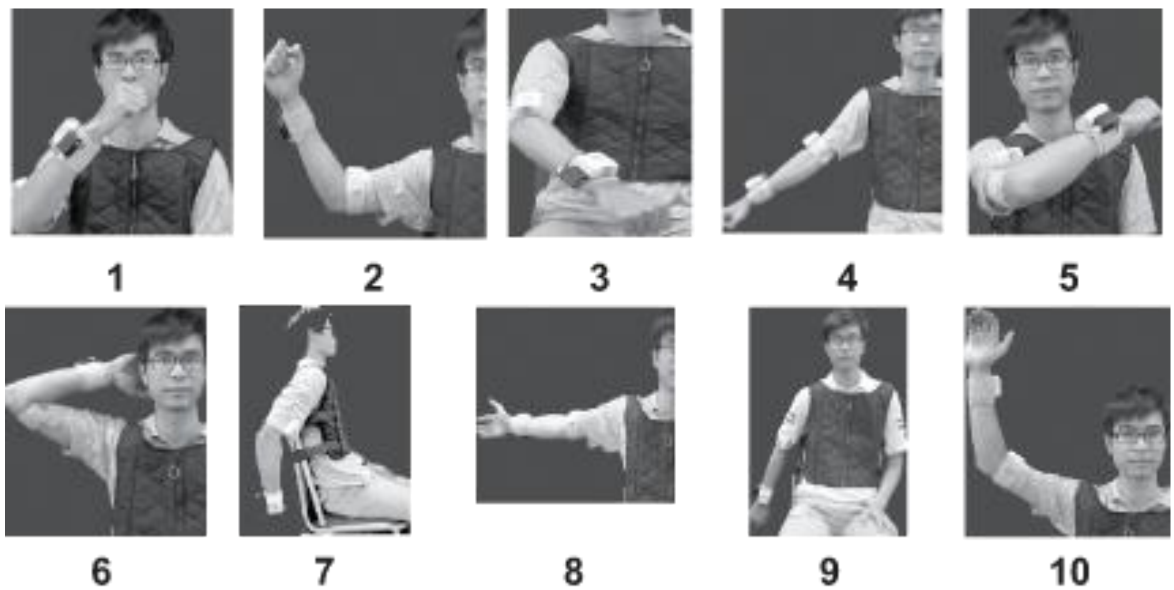


Figure 5- 6: The 10 postures used in the experiments

5.3 Results and discussion

We compared the performance of using the four feedback configurations in correcting the arm posture by looking at the total mapping time (how long it takes to replicate a posture) and accuracy w.r.t. to each parameter of the reference posture.

a. Mapping time

Figure 5-7 shows the graph of the average mapping time of ten subjects for every feedback module. A considerable difference between using visual cue alone and the rest of the feedback modes exist. The mapping time of relying on visual cue alone is the shortest across all postures at 6.29s, as listed in Table 5-2 (V+T(s) is series visuotactile, V+T(p) is parallel visuotactile, T is vibrotactile only, and V is visual cue only). The feedback mode that allows the fastest mapping time among the other modes is the visual cue and vibrotactile in series ($V + T\ (s)$) at 30.72s. It also has the lowest error for any parameter for all postures. Visual cue and vibrotactile feedback in parallel ($V + T$ (p)) provides slightly better performance than when relying only on vibrotactile. The former has an average mapping time of 39.71 s while the latter has 45.98 s.

Table 5- 2: Average mapping time of ten subjects for the ten postures with 4 different feedback modes

Feedback Mode	Mapping Time (s)
V+T(s)	30.72 ± 12.53
V+T(p)	39.71 ± 19.82
T	45.98 ± 17.00
V	6.29 ± 4.65

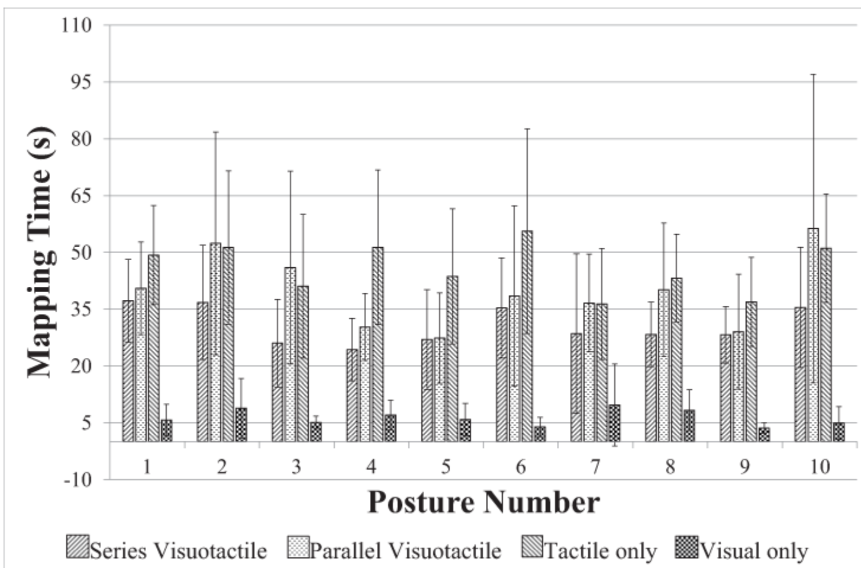


Figure 5- 7: Average mapping time of 10 subjects for 10 postures

b. Mapping accuracy

During the experiments, the subjects assume the arm posture which they think is nearest to the reference posture. They announce once they decide that they have achieved the desired posture and the time is recorded. The "Visual cue and vibrotactile in series" mode gives the lowest accuracy among the averages of the four feedback modes as listed in Table 5-3 and illustrated in Fig.5-8, 5-9, 5-10 which show the graphs of the error for the wrist, the elbow, and the forearm across all postures.

Table 5- 3: Average error of 10 subjects for the 10 postures

Error	V+T(s)	V+T(p)	T	V
Wrist position (mm)	19.18 ± 6.00	21.28 ± 5.41	21.82 ± 4.96	89.35 ± 34.31
Elbow position (mm)	17.81 ± 6.73	19.23 ± 6.35	17.85 ± 6.49	63.91 ± 26.55
Forearm roll (deg)	6.58 ± 3.27	6.99 ± 3.03	6.91 ± 2.69	22.22 ± 14.47

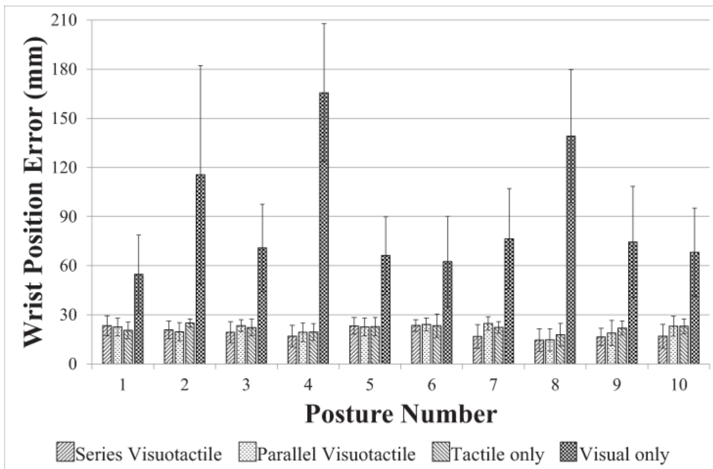


Figure 5- 8: Wrist position error of 10 subjects for 10 postures

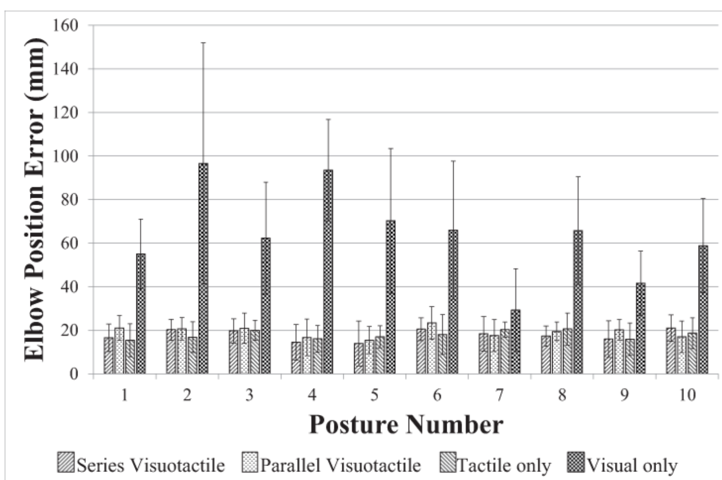


Figure 5- 9: Elbow position error of 10 subjects for 10 postures

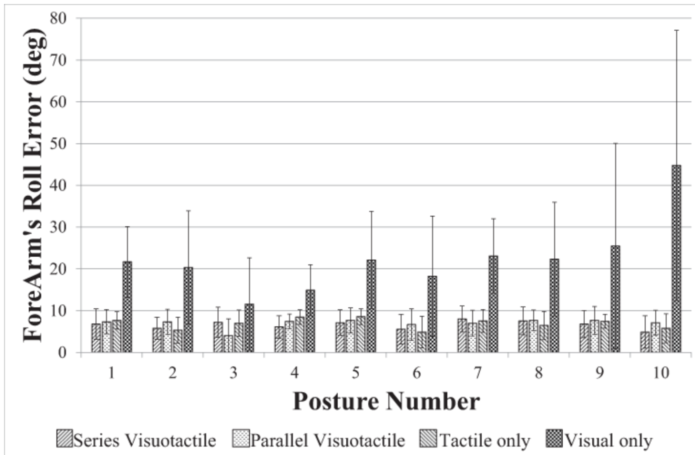


Figure 5- 10: Forearm roll error of 10 subjects for 10 postures

Based on the results, visual cue may be viewed as feedback for posture correction on a global level (gross motion) and vibrotactile feedback for finer level (fine motion). If global feedback alone is used, subjects cannot fine tune of their posture (such as in the case of *V)*. If the two modes are combined properly, they enable better posture correction performance.

Comparing feedback modes *V +T* (*s*) and *V +T* (*p*), the better performance of the series configuration might be due to interference between the feedback channels. The presence of visual cue while following the vibrotactile feedback (parallel) could divide attention which might cause the subject to overshoot past the reference posture, lengthening posture correction time. However, in series configuration the subject is given just enough global information to limit the search space for the wrist position, but not enough to actually interfere with the vibrotactile feedback.

c. Conclusion

Except the "visual cue only" mode that results large error in performance, the series visuotactile mode provides slightly better mapping time. It is faster ~9s compared to parallel visuotactile mode, ~15s compared to tactile only mode. The mapping accuracy is approximately the same among 3 modes.

Chapter 6: Conclusion and Future Work

6.1 Discussion and Conclusion

There is significant number of people suffering from stroke each year. For those who survive, the ability to carry out skilled upper limb movement are afflicted with motor control problem. Hence, it is necessary to provide them rehab exercises to recover the upper limb's movement. Most rehabilitation involves having the patients repeat arm movements or train to achieve correct different arm postures. Due to the increasing number of patients in rehabilitation centers, developing a home-based low cost device is valuable and important for arm posture replication and rehabilitation. In this report, a new protocol, different strategies of utilizing vibrotactile feedback, software development for the arm posture replication are presented. In particular, the main focus of project is to investigate the best strategy in term of mapping time and accuracy for an integrated system comprising IMU and vibrotactile feedback in arm posture replication. Additionally, the consideration was extended with the combination of vibrotactile feedback and visual feedback (visuotactile feedback) as better solution for arm posture replication. Fig.6-1 shows the subject wearing the integrated system (IMUs and Vibrotactile unit) for arm posture replication process.

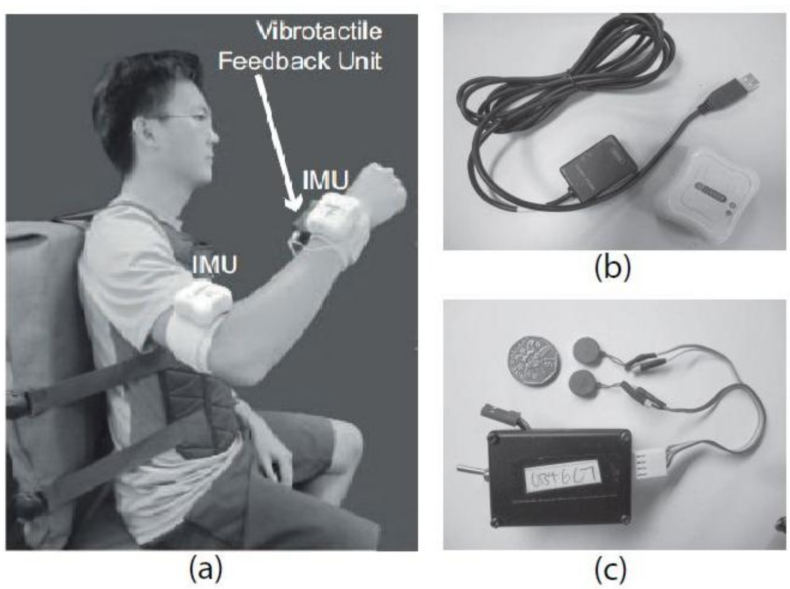


Figure 6- 1: Subject with integrated system for arm posture replication: (a) experiment set-up, (b) IMU and (c) Vibrotactile unit

Basically, the objective of this project has been met as the new protocol has been implemented successfully for arm posture replication, by evaluating the mapping time and the accuracy. Moreover, the best strategy for posture replication with new protocol has been investigated. The major tasks carried in the project are summarised as follows:

(a) New protocol for arm posture replication

One arm posture is replicated following three parameters: the wrist position, the elbow position and the forearm's roll in sequence. The protocol can be considered to be more natural than previous posture correction strategies that the arm posture was corrected one parameter at a time starting from the shoulder to the forearm. The process is more mechanical compared to the new approach. The kinematic formulation was developed for determination of the wrist and the elbow positions. Using the kinematic; a GUI software has been developed successful as control system for the integrated system with IMU and vibrotactile.

(b) Use of vibrotactile sensor as directional or matching error indicators

Two different ways of using vibrotactile feedback for arm posture replication is discussed. First is the use of vibrotactile feedback as directional indicator in posture correction. Multiple vibrotactile motors are positioned on either stationary or moving arm of the subject to provide consistent directional feedback on the moving arm. Secondly, the vibrotactile feedback is used as matching error indicator that informs the user the magnitude of error between the current posture and the target posture. The experiment is conducted with 7 people to replicate 5 different postures. The results show that: the directional feedback on stationary arm provides better performance compared to using it on moving arm (faster ~6s to complete the posture correction; however, the mapping errors between two approaches, either on stationary or moving arm are comparable). And the usage of vibrotactile feedback as matching error indicator enables faster (~16s) and more accurate (~8mm for wrist position) arm posture correction than the directional feedback on moving arm.

(c) Evaluation of combinations of visual and vibrotactile feedback

Four different combinations of vibrotactile and visual cue feedback were tested: visual only, tactile only, series visuotactile (visual and tactile in series), and parallel visuotactile (visual and tactile in parallel). The experiment is conducted with 10 people to replicate 10 different postures. Results showed that, the series visuotactile mode provides slightly better mapping time. It is faster ~9s compared to parallel visuotactile mode, ~15s compared to tactile only mode. The mapping accuracy is approximately the same among 3 modes.

6.2 Future work

There are several recommendations summarized for future work:

- This designed tactile feedback system can be also used by other body segments such as the legs and trunk. However, the skin sensitivity in different body segments is very different. One possible solution that can tackle this issue is to develop different vibration patterns (varying vibration strength or period) that are suitable for a particular segment.

- A consideration for future work is combining active visual feedback instead of just visual cues and adding additional feedback channel (audio).

- The comparison between non-directional and directional vibrotactile feedback can be evaluated by incorporating vision feedback instead of only vibrotactile feedback.

- Additionally, work is currently underway in designing rehab modules that use vibrotactile feedback for use in actual stroke rehabilitation.

By understanding the dynamics of vibrotactile feedback in posture replication, we hope to contribute to design improvements of robotic systems in rehabilitation. This in turn could help realize home-based and patient-initiated health care especially in stroke rehabilitation.

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Appendix A

Personal information of ten subjects for "Different Combinations of Visual and Vibrotactile Feedback" experiment

Subject	Age	Sex	Occupation	Health Status	Remarks
1	21	F	Student	Good	Studying in NTU
2	23	F	Student	Good	Studying in NTU
3	24	F	Student	Good	Studying in NTU
4	22	F	Student	Good	Studying in NTU
5	22	F	Student	Good	Studying in NTU
6	23	M	Student	Good	Studying in NTU
7	25	M	Student	Good	Studying in NTU
8	24	M	Student	Good	Studying in NTU
9	24	M	Student	Good	Studying in NTU
10	20	M	Student	Good	Studying in NTU

Personal information of seven subjects for "Usage of Vibrotactile Feedback as Direction and Matching Error Indicator" experiment

Subject	Age	Sex	Occupation	Health Status	Remarks
1	21	F	Student	Good	Studying in NTU
2	20	F	Student	Good	Studying in NTU
3	22	F	Student	Good	Studying in NTU
4	24	F	Student	Good	Studying in NTU
5	25	M	Student	Good	Studying in NTU
6	23	M	Student	Good	Studying in NTU
7	22	M	Student	Good	Studying in NTU

Appendix B

The Usage of Vibrotactile Feedback as Directional Indicator on Moving Arm – Chapter 4

Posture Index	**Student Index**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	Wrist position error (mm)	15.36	36.91	95.53	45.62	50.04	35.13	33.76
	Elbow position error (mm)	16.06	24.00	19.95	24.69	24.37	33.38	23.35
	Forearm's roll error (deg)	8.00	9.00	7.00	8.00	1.00	9.00	9.00
	Mapping time (sec)	91.39	45.57	62.93	66.20	79.96	29.66	80.71
2	Wrist position error (mm)	39.16	21.19	17.03	45.22	51.72	60.65	41.20
	Elbow position error (mm)	17.51	22.00	12.04	22.72	8.31	22.47	19.55
	Forearm's roll error (deg)	5.40	4.00	4.00	8.00	9.00	2.00	7.00
	Mapping time (sec)	54.90	61.95	61.05	43.89	75.33	32.31	56.94
3	Wrist position error (mm)	69.82	37.71	24.04	19.10	8.80	40.91	34.80
	Elbow position error (mm)	26.34	18.79	9.00	24.78	4.00	28.39	19.95
	Forearm's roll error (deg)	8.00	10.00	9.00	3.00	7.80	6.00	9.00
	Mapping time (sec)	32.66	48.52	26.90	40.40	53.16	25.23	39.21
4	Wrist position error (mm)	6.32	48.06	3.16	1.86	18.11	20.02	47.47
	Elbow position error (mm)	6.16	24.10	11.05	9.75	9.90	22.67	22.70
	Forearm's roll error (deg)	10.00	9.00	9.00	7.70	10.00	1.00	6.00
	Mapping time (sec)	32.18	56.06	48.47	47.17	63.22	27.75	43.01
5	Wrist position error (mm)	33.08	46.50	16.40	41.26	50.84	9.70	19.75
	Elbow position error (mm)	29.32	7.07	31.72	45.83	48.36	12.12	16.79
	Forearm's roll error (deg)	8.00	9.00	7.00	8.00	7.00	6.00	1.00
	Mapping time (sec)	62.40	61.20	67.62	58.40	43.13	28.55	101.48

The Usage of Vibrotactile Feedback as Directional Indicator on Stationary Arm – Chapter 4

Posture Index	**Student Index**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	Wrist position error (mm)	29.23	10.05	26.93	39.15	12.81	35.81	26.83
	Elbow position error (mm)	21.02	14.04	24.29	26.65	10.63	17.94	19.10
	Forearm’s roll error (deg)	1.00	4.00	9.00	7.00	2.00	4.00	5.00
	Mapping time (sec)	37.54	52.01	63.01	31.30	49.20	37.85	45.15
2	Wrist position error (mm)	29.70	54.34	50.64	41.82	50.55	31.84	33.84
	Elbow position error (mm)	18.03	29.60	26.05	31.46	21.93	31.26	24.04
	Forearm’s roll error (deg)	10.00	10.00	7.00	9.00	8.00	4.00	8.00
	Mapping time (sec)	37.46	58.55	87.34	73.85	52.65	51.73	48.27
3	Wrist position error (mm)	13.09	28.18	27.33	36.03	36.85	38.95	27.74
	Elbow position error (mm)	15.52	21.58	10.82	11.05	13.04	16.28	15.88
	Forearm’s roll error (deg)	9.00	10.00	7.00	10.00	9.00	8.00	9.00
	Mapping time (sec)	33.28	52.63	35.03	36.19	25.82	58.30	41.37
4	Wrist position error (mm)	18.79	41.91	61.60	44.38	50.52	50.07	43.38
	Elbow position error (mm)	17.92	24.48	22.29	24.93	31.70	27.28	25.93
	Forearm’s roll error (deg)	10.00	9.00	10.00	8.00	8.00	4.00	8.00
	Mapping time (sec)	36.07	47.03	52.37	46.71	44.81	56.26	43.71
5	Wrist position error (mm)	20.90	33.91	18.29	25.81	33.62	46.52	31.01
	Elbow position error (mm)	22.16	24.43	22.49	14.76	20.98	30.41	26.04
	Forearm’s roll error (deg)	2.00	9.00	10.00	10.00	9.00	0.00	7.00
	Mapping time (sec)	34.64	46.76	68.44	29.12	33.12	49.11	41.20

The Usage of Vibrotactile Feedback as Matching Error Information Indicator – Chapter 4

Posture Index	**Student Index**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	Wrist position error (mm)	10.52	32.71	50.92	36.07	11.36	35.28	35.31
	Elbow position error (mm)	10.72	29.66	23.54	10.39	20.02	24.21	24.42
	Forearm's roll error (deg)	8.00	8.00	10.00	9.00	5.00	4.00	11.00
	Mapping time (sec)	10.94	46.17	11.93	16.10	7.96	19.00	17.52
2	Wrist position error (mm)	36.04	23.34	15.59	24.08	36.18	15.52	33.63
	Elbow position error (mm)	18.28	18.23	21.56	22.52	17.20	10.20	26.60
	Forearm's roll error (deg)	6.00	8.00	5.00	8.00	8.00	5.00	4.00
	Mapping time (sec)	43.09	41.90	82.95	29.08	71.42	34.66	19.51
3	Wrist position error (mm)	22.00	4.12	29.22	26.25	19.34	22.56	24.08
	Elbow position error (mm)	21.10	8.12	4.58	23.49	10.82	24.54	13.11
	Forearm's roll error (deg)	9.00	7.00	3.00	6.00	7.00	10.00	10.00
	Mapping time (sec)	43.09	75.65	16.75	40.85	53.61	32.44	40.23
4	Wrist position error (mm)	22.00	4.12	29.22	26.25	19.34	22.56	24.08
	Elbow position error (mm)	21.10	8.12	4.58	23.49	10.82	24.54	13.11
	Forearm's roll error (deg)	9.00	7.00	3.00	6.00	7.00	10.00	11.00
	Mapping time (sec)	43.09	75.65	16.75	40.85	53.61	32.44	40.23
5	Wrist position error (mm)	6.56	48.77	8.81	44.03	25.08	18.47	24.12
	Elbow position error (mm)	25.11	33.48	28.44	27.39	8.06	24.43	22.15
	Forearm's roll error (deg)	8.00	10.00	5.00	7.00	5.00	1.00	8.00
	Mapping time (sec)	48.46	45.68	35.39	38.55	14.28	29.75	35.35

Appendix C

Investigation of Different Combinations of Visual and Vibrotactile Feedback – Chapter 5

Visual Cue Feedback only

Posture Index	Student Index	1	2	3	4	5	6	7	8	9	10
1	Wrist position error (mm)	87.69	35.07	62.44	36.07	66.05	18.97	45.81	50.29	115.29	89.77
	Elbow position error (mm)	69.84	45.72	60.70	50.00	68.01	29.29	46.91	44.31	71.68	80.85
	Forearm's roll error (deg)	31.00	25.00	11.00	23.00	11.00	30.00	18.00	32.00	0.00	14.00
	Mapping time (sec)	9.04	1.50	8.34	1.50	6.83	2.04	7.40	12.99	1.68	1.83
2	Wrist position error (mm)	216.56	197.32	15.65	150.00	100.11	133.73	89.40	99.50	65.89	37.01
	Elbow position error (mm)	163.13	181.04	24.25	140.00	79.57	77.01	69.89	104.28	59.45	30.43
	Forearm's roll error (deg)	23.00	22.00	14.00	22.00	45.00	24.00	1.00	30.00	25.00	2.00
	Mapping time (sec)	3.71	2.73	16.92	2.73	12.59	24.34	2.03	10.37	1.53	4.08
3	Wrist position error (mm)	47.54	45.62	58.62	54.00	90.14	104.72	118.47	63.42	111.00	55.36
	Elbow position error (mm)	71.13	34.79	73.99	45.00	101.32	92.03	50.01	67.74	114.32	24.19
	Forearm's roll error (deg)	3.00	4.00	3.00	6.00	21.00	21.00	5.00	7.00	41.00	34.00
	Mapping time (sec)	4.64	5.86	3.19	5.86	7.08	7.09	1.89	4.85	1.68	5.07
4	Wrist position error (mm)	215.65	125.65	110.61	126.00	229.48	149.19	181.58	194.67	224.70	158.09
	Elbow position error (mm)	124.30	75.95	54.53	76.00	115.56	83.65	115.59	107.04	124.34	88.98
	Forearm's roll error (deg)	9.00	15.00	7.00	15.00	10.00	12.00	25.00	22.00	93.00	19.00
	Mapping time (sec)	7.32	8.22	16.07	8.22	3.32	6.61	4.28	6.58	22.53	2.78
5	Wrist position error (mm)	102.49	68.06	71.20	50.00	96.69	37.27	55.31	36.36	94.39	78.39
	Elbow position error (mm)	95.29	107.28	55.66	106.28	93.19	78.92	41.45	17.58	34.15	36.73
	Forearm's roll error (deg)	10.00	17.00	11.00	17.00	23.00	49.00	25.00	20.00	8.00	27.00

	Mapping time (sec)	3.10	5.64	4.36	5.64	5.00	6.41	2.23	3.70	1.49	16.68
6	Wrist position error (mm)	41.30	110.32	65.91	90.00	40.79	70.75	17.72	57.53	43.66	67.51
	Elbow position error (mm)	94.01	62.04	95.88	64.04	113.48	64.62	25.65	17.23	115.84	56.74
	Forearm’s roll error (deg)	13.00	41.00	4.00	42.00	12.00	24.00	9.00	5.00	5.00	14.00
	Mapping time (sec)	2.66	3.96	2.85	3.96	10.22	1.54	2.45	4.56	2.00	2.88
7	Wrist position error (mm)	94.76	105.30	28.67	120.00	47.13	74.07	96.66	73.91	57.76	47.20
	Elbow position error (mm)	31.62	16.82	26.48	13.82	57.15	3.32	53.12	15.39	78.16	45.73
	Forearm’s roll error (deg)	10.00	29.00	19.00	40.00	16.00	17.00	25.00	23.00	1.00	29.00
	Mapping time (sec)	13.87	4.48	5.08	4.48	7.61	3.96	3.92	37.33	3.20	6.72
8	Wrist position error (mm)	154.74	117.51	123.85	117.51	165.39	180.50	196.22	61.46	105.55	135.13
	Elbow position error (mm)	66.91	47.92	51.93	47.92	68.32	111.85	97.56	35.69	35.61	63.85
	Forearm’s roll error (deg)	29.00	37.00	18.00	37.00	16.00	40.00	8.00	11.00	21.00	5.00
	Mapping time (sec)	2.34	4.55	11.61	4.55	10.36	5.32	3.67	15.41	6.69	16.94
9	Wrist position error (mm)	134.36	46.40	61.82	50.00	52.39	51.24	62.26	85.04	97.71	126.92
	Elbow position error (mm)	55.44	45.85	13.93	44.85	46.44	24.88	53.65	31.92	52.01	56.94
	Forearm’s roll error (deg)	44.00	2.00	50.00	5.00	6.00	11.00	5.00	67.00	65.00	39.00
	Mapping time (sec)	4.04	2.93	3.66	2.93	5.99	2.89	1.07	3.12	2.92	5.46
10	Wrist position error (mm)	115.70	40.72	47.78	43.00	81.16	73.91	90.98	81.80	53.91	38.34
	Elbow position error (mm)	107.66	43.51	48.18	41.51	46.37	41.00	65.65	71.72	34.89	63.73
	Forearm’s roll error (deg)	22.00	34.00	1.00	39.00	97.00	42.00	38.00	32.00	1.00	98.00
	Mapping time (sec)	3.78	3.74	3.78	3.74	8.32	15.13	1.30	2.79	2.09	1.64

Vibrotactile Feedback only

Posture Index	Student Index	1	2	3	4	5	6	7	8	9	10
1	Wrist position error (mm)	24.03	15.81	22.00	23.75	22.28	15.07	12.04	27.08	26.34	22.20
	Elbow position error (mm)	17.66	23.00	12.88	25.09	14.04	9.70	22.85	1.41	21.02	12.33
	Forearm’s roll error (deg)	6.00	10.00	10.00	5.00	8.00	10.00	7.00	8.00	0.00	5.00
	Mapping time (sec)	41.48	69.09	40.43	49.14	53.57	48.00	34.73	36.42	20.03	70.46
2	Wrist position error (mm)	24.03	15.81	22.00	23.75	22.28	15.07	12.04	27.08	26.34	22.20
	Elbow position error (mm)	17.66	23.00	12.88	25.09	14.04	9.70	22.85	1.41	21.02	12.33
	Forearm’s roll error (deg)	6.00	10.00	10.00	5.00	8.00	10.00	7.00	8.00	0.00	5.00
	Mapping time (sec)	41.48	69.09	40.43	49.14	53.57	48.00	34.73	36.42	20.03	70.46
3	Wrist position error (mm)	25.03	21.24	27.10	21.42	25.79	17.32	28.52	21.21	4.36	12.57
	Elbow position error (mm)	21.47	24.78	25.09	26.44	15.56	18.79	16.03	17.29	4.24	14.04
	Forearm’s roll error (deg)	6.00	10.00	4.00	10.00	6.00	10.00	9.00	7.00	0.00	1.00
	Mapping time (sec)	68.99	26.35	60.92	15.63	29.69	55.37	34.28	54.30	74.57	23.97
4	Wrist position error (mm)	24.80	22.23	25.38	22.05	19.85	13.27	15.07	21.66	25.89	11.18
	Elbow position error (mm)	19.08	17.72	21.35	23.56	11.05	12.25	3.74	20.45	16.64	15.03
	Forearm’s roll error (deg)	8.00	10.00	10.00	10.00	10.00	8.00	7.00	5.00	5.00	8.00
	Mapping time (sec)	66.24	47.47	43.85	21.42	45.14	90.48	67.68	34.98	30.74	44.72
5	Wrist position error (mm)	24.76	22.07	24.84	11.18	29.59	26.23	25.14	17.12	17.75	24.39
	Elbow position error (mm)	22.02	25.40	9.43	20.22	14.90	15.36	12.04	14.56	10.86	18.63
	Forearm’s roll error (deg)	9.00	10.00	8.00	4.00	10.00	10.00	9.00	9.00	10.00	8.00
	Mapping time (sec)	41.39	81.58	42.08	22.76	34.30	44.96	25.58	40.97	39.94	59.22
6	Wrist position error (mm)	10.86	28.00	17.03	18.03	24.18	27.66	35.02	25.09	39.09	23.52
	Elbow position error (mm)	16.28	22.69	21.02	26.39	25.59	2.24	24.08	3.46	27.95	20.32
	Forearm’s roll error (deg)	1.00	10.00	6.00	2.00	0.00	10.00	6.00	2.00	2.00	7.00

	Mapping time (sec)	13.86	50.39	46.63	102.56	60.17	52.78	91.60	36.20	42.25	46.20
7	Wrist position error (mm)	21.47	21.47	15.81	25.36	27.08	22.00	18.89	25.63	25.01	23.35
	Elbow position error (mm)	24.92	22.83	22.47	18.76	15.43	16.91	20.81	23.85	24.63	16.88
	Forearm's roll error (deg)	9.00	6.00	9.00	10.00	8.00	8.00	9.00	8.00	5.00	1.00
	Mapping time (sec)	44.60	49.34	13.26	64.43	30.17	28.56	35.36	31.23	60.03	30.02
8	Wrist position error (mm)	24.87	27.76	23.22	11.75	18.25	21.63	12.45	11.49	NA	8.54
	Elbow position error (mm)	27.18	24.72	20.86	21.24	21.83	24.64	25.61	3.16	NA	15.78
	Forearm's roll error (deg)	6.00	3.00	1.00	8.00	10.00	9.00	10.00	8.00	NA	3.00
	Mapping time (sec)	32.06	31.10	42.89	53.29	52.30	39.44	61.00	49.25	NA	27.39
9	Wrist position error (mm)	24.91	15.84	20.58	24.60	25.05	23.69	25.30	13.64	26.16	23.62
	Elbow position error (mm)	21.47	24.86	16.09	11.75	8.06	16.76	23.07	2.00	23.26	18.55
	Forearm's roll error (deg)	5.00	6.00	7.00	6.00	10.00	9.00	9.00	8.00	1.00	7.00
	Mapping time (sec)	37.59	21.57	24.54	61.33	41.94	40.41	37.14	40.03	56.16	28.06
10	Wrist position error (mm)	24.12	25.31	24.29	27.13	26.45	24.65	13.75	17.03	NA	24.07
	Elbow position error (mm)	17.49	22.58	20.32	12.25	21.61	26.00	24.08	3.00	NA	20.52
	Forearm's roll error (deg)	1.00	6.00	5.00	9.00	10.00	10.00	6.00	4.00	NA	1.00
	Mapping time (sec)	60.17	31.23	62.23	53.47	37.29	67.11	56.41	30.12	NA	61.91

Visual Cue and Vibrotactile in Series

Posture Index	Student Index	1	2	3	4	5	6	7	8	9	10
1	Wrist position error (mm)	24.49	23.54	22.09	22.13	20.12	22.25	28.59	34.68	24.78	12.08
	Elbow position error (mm)	10.05	18.79	13.75	14.18	23.62	23.56	19.21	20.83	6.63	5.10
	Forearm's roll error (deg)	1.00	10.00	1.00	10.00	6.00	9.00	10.00	8.00	2.00	6.00
	Mapping time (sec)	29.56	56.08	27.76	53.39	24.17	36.85	36.13	32.27	30.03	38.53
2	Wrist position error (mm)	24.43	23.09	12.25	23.31	24.21	21.22	25.48	22.74	16.42	10.82
	Elbow position error (mm)	25.36	20.40	14.25	13.93	24.27	14.18	23.85	24.32	2.00	21.59
	Forearm's roll error (deg)	6.00	2.00	7.00	3.00	5.00	10.00	9.00	6.00	8.00	4.00
	Mapping time (sec)	52.70	36.44	28.67	41.01	37.88	66.42	23.72	19.71	18.37	24.64
3	Wrist position error (mm)	20.69	27.49	21.19	12.65	14.32	22.83	23.22	24.27	14.14	7.07
	Elbow position error (mm)	18.03	25.46	13.78	11.70	16.03	24.60	27.68	22.00	22.69	17.94
	Forearm's roll error (deg)	6.00	0.00	3.00	8.00	10.00	10.00	10.00	8.00	1.00	10.00
	Mapping time (sec)	29.56	52.97	17.80	12.87	24.33	21.82	28.59	28.28	32.75	17.78
4	Wrist position error (mm)	12.45	20.32	22.47	17.38	21.00	11.22	3.74	24.19	24.88	19.44
	Elbow position error (mm)	7.00	21.66	25.27	18.49	7.81	20.74	1.41	18.25	10.82	10.00
	Forearm's roll error (deg)	2.00	9.00	7.00	3.00	5.00	6.00	10.00	5.00	9.00	8.00
	Mapping time (sec)	15.40	36.60	37.71	26.11	24.27	18.67	24.93	15.57	15.51	19.37
5	Wrist position error (mm)	25.07	27.90	15.17	23.15	27.39	21.03	15.39	28.22	21.03	25.85
	Elbow position error (mm)	2.00	25.51	20.10	22.23	8.00	0.00	18.71	24.54	0.00	4.00
	Forearm's roll error (deg)	3.00	10.00	10.00	10.00	10.00	4.00	8.00	5.00	4.00	4.00
	Mapping time (sec)	18.44	19.08	45.63	19.37	38.72	11.63	43.91	14.32	11.63	31.82
6	Wrist position error (mm)	24.07	21.05	23.72	27.23	15.39	25.10	25.72	22.56	25.10	25.96
	Elbow position error (mm)	20.49	24.35	22.11	23.52	24.62	23.77	9.43	13.93	23.77	21.91
	Forearm's roll error (deg)	4.00	9.00	2.00	3.00	3.00	5.00	3.00	12.00	5.00	9.00

	Mapping time (sec)	37.80	26.32	31.88	43.98	14.51	21.75	58.11	43.53	21.75	40.03
7	Wrist position error (mm)	3.16	19.95	18.00	15.17	22.14	25.69	16.16	8.12	27.84	22.94
	Elbow position error (mm)	23.02	11.18	10.20	17.49	24.31	23.04	5.39	21.63	26.09	29.55
	Forearm’s roll error (deg)	8.00	1.00	10.00	8.00	10.00	10.00	10.00	10.00	10.00	5.00
	Mapping time (sec)	20.38	11.00	16.37	30.58	65.62	62.40	11.61	13.65	22.96	25.34
8	Wrist position error (mm)	1.73	13.93	10.82	15.13	18.03	27.59	16.97	11.00	17.03	15.26
	Elbow position error (mm)	24.86	14.63	8.60	20.64	14.63	16.43	19.95	18.38	25.42	18.28
	Forearm’s roll error (deg)	2.00	10.00	10.00	8.00	10.00	9.00	7.00	2.00	2.00	10.00
	Mapping time (sec)	20.08	18.12	43.68	25.98	39.33	29.32	22.01	26.04	16.25	30.50
9	Wrist position error (mm)	12.69	20.85	21.73	16.03	13.64	13.19	26.17	13.89	28.80	9.85
	Elbow position error (mm)	12.85	24.27	10.63	18.06	25.08	14.25	27.68	5.10	22.98	5.48
	Forearm’s roll error (deg)	2.00	9.00	10.00	3.00	9.00	8.00	10.00	3.00	10.00	7.00
	Mapping time (sec)	25.49	36.66	22.77	21.91	16.45	39.35	26.94	32.09	36.23	32.36
10	Wrist position error (mm)	24.20	10.12	24.54	19.95	11.66	22.13	12.04	5.10	21.93	23.04
	Elbow position error (mm)	8.72	15.13	18.25	19.80	25.36	26.93	25.36	24.44	1.00	25.14
	Forearm’s roll error (deg)	3.00	9.00	5.00	2.00	4.00	10.00	1.00	10.00	9.00	0.00
	Mapping time (sec)	29.53	20.63	45.34	25.61	52.00	49.33	18.21	19.61	22.22	58.81

Visual Cue and Vibrotactile in Parallel

Posture Index	Student Index	1	2	3	4	5	6	7	8	9	10
1	Wrist position error (mm)	27.64	28.16	25.24	22.87	9.80	24.17	22.64	20.32	19.42	22.08
	Elbow position error (mm)	19.65	31.30	21.05	18.49	15.65	24.84	20.81	12.04	12.73	25.38
	Forearm's roll error (deg)	7.00	8.00	8.00	0.00	9.00	8.00	10.00	9.00	8.00	7.00
	Mapping time (sec)	41.88	56.76	31.10	44.05	58.33	18.12	38.15	37.14	26.86	39.06
2	Wrist position error (mm)	23.37	24.02	24.47	7.07	15.59	20.12	20.27	18.03	25.73	23.52
	Elbow position error (mm)	19.34	24.37	19.24	14.32	30.79	20.62	17.92	24.21	21.12	15.13
	Forearm's roll error (deg)	4.00	4.00	10.00	9.00	11.00	8.00	7.00	10.00	6.00	3.00
	Mapping time (sec)	54.65	117.63	21.60	39.37	47.27	53.22	73.06	20.59	26.77	43.82
3	Wrist position error (mm)	19.26	27.92	16.28	21.63	24.68	25.12	24.60	25.39	24.23	25.50
	Elbow position error (mm)	26.15	24.41	27.37	24.98	8.54	25.50	15.91	12.04	17.94	23.43
	Forearm's roll error (deg)	8.00	3.00	0.00	0.00	0.00	3.00	9.00	3.00	0.00	10.00
	Mapping time (sec)	42.21	86.58	36.26	43.72	19.27	85.99	53.56	21.28	16.68	25.05
4	Wrist position error (mm)	24.15	20.64	24.74	25.03	13.49	20.20	13.49	21.84	23.94	10.25
	Elbow position error (mm)	16.88	13.93	20.66	24.35	25.67	9.90	27.68	4.69	22.06	6.71
	Forearm's roll error (deg)	8.00	7.00	8.00	9.00	8.00	7.00	10.00	4.00	8.00	6.00
	Mapping time (sec)	42.17	27.09	26.52	32.86	45.48	19.93	31.02	27.67	35.12	20.02
5	Wrist position error (mm)	24.94	11.87	17.12	20.59	21.56	27.91	27.92	25.68	20.10	26.14
	Elbow position error (mm)	15.56	27.96	13.19	15.91	10.63	7.28	14.53	11.45	25.42	22.11
	Forearm's roll error (deg)	1.00	9.00	7.00	10.00	10.00	10.00	9.00	8.00	3.00	5.00
	Mapping time (sec)	27.20	49.21	15.32	21.94	20.14	35.93	40.66	16.04	49.68	19.94
6	Wrist position error (mm)	23.35	25.82	17.09	23.59	25.63	25.27	25.61	30.79	16.61	19.39
	Elbow position error (mm)	24.91	24.76	25.00	25.08	3.74	25.44	27.53	28.64	24.04	25.04
	Forearm's roll error (deg)	2.00	10.00	7.00	4.00	9.00	8.00	10.00	0.00	1.00	10.00

	Mapping time (sec)	13.06	58.78	16.83	31.83	37.51	26.85	89.48	46.48	14.74	25.58
7	Wrist position error (mm)	24.57	27.16	21.95	20.83	20.83	19.95	28.75	31.91	24.27	25.98
	Elbow position error (mm)	23.86	25.10	11.58	14.53	20.83	27.43	4.69	16.03	12.33	14.32
	Forearm's roll error (deg)	8.00	3.00	9.00	10.00	8.00	9.00	1.00	9.00	6.00	6.00
	Mapping time (sec)	56.82	52.82	34.77	28.96	24.02	46.65	34.66	31.97	19.21	18.92
8	Wrist position error (mm)	14.14	24.06	7.35	17.12	20.90	12.96	2.24	19.72	22.35	13.38
	Elbow position error (mm)	23.37	21.35	15.13	20.71	19.39	23.28	22.69	10.39	24.70	18.63
	Forearm's roll error (deg)	9.00	10.00	8.00	10.00	3.00	9.00	6.00	9.00	0.00	5.00
	Mapping time (sec)	30.53	62.03	31.21	20.63	34.97	76.50	34.02	38.64	30.29	32.71
9	Wrist position error (mm)	19.65	22.37	24.12	12.37	25.18	25.72	23.29	3.00	36.13	14.42
	Elbow position error (mm)	23.96	25.63	16.58	15.52	27.71	20.62	15.23	15.78	10.44	20.88
	Forearm's roll error (deg)	8.00	10.00	9.00	2.00	8.00	10.00	10.00	10.00	1.00	2.00
	Mapping time (sec)	46.58	26.87	15.56	13.86	60.44	26.12	26.95	26.62	34.22	18.35
10	Wrist position error (mm)	25.50	24.55	22.76	27.29	24.73	25.97	25.48	24.01	22.58	7.35
	Elbow position error (mm)	17.52	26.39	18.49	7.81	25.98	13.64	6.16	22.56	24.90	14.28
	Forearm's roll error (deg)	10.00	4.00	6.00	5.00	2.00	8.00	9.00	10.00	3.00	10.00
	Mapping time (sec)	136.25	54.45	12.43	89.99	23.13	19.37	83.18	30.38	28.85	57.49